NATIONAL TRANSPORTATION SAFETY BOARD

Office of Research and Engineering
Washington, D.C. 20594

March 29, 2012

Aircraft Performance Study Addendum #1

by John O'Callaghan

ACCIDENT:

Location: Roswell, New Mexico
Date: April 2, 2011
Time: 09:34 Mountain Daylight Time (MDT)
Aircraft: Gulfstream Aerospace Corporation GVI (G650), registration N652GD
NTSB#: DCA11MA076

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A. ACCIDENT

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[1] Unless otherwise noted, all times in this *Addendum* are based on a 24-hour clock in MDT. MDT = Universal Coordinated Time (UTC) - 6 hours.

C. HISTORY OF FLIGHT

On April 2, 2011, about 0934 mountain daylight time, an experimental Gulfstream Aerospace Corporation (GAC) GVI (G650)[2], registration N652GD, serial number 6002, crashed during takeoff from runway 21 at Roswell International Air Center Airport (ROW), Roswell, New Mexico. The flight was being operated by the manufacturer as part of its G650 developmental field performance flight test program. The two pilots and the two flight test engineers were fatally injured, and the airplane was substantially damaged. The flight was being conducted under 14 *Code of Federal Regulations* Part 91, and visual meteorological conditions prevailed at the time of the accident.

The *Aircraft Performance Study* for this accident (Reference 1) presents the results of using ground scars and markings, recorded flight data, weather information, and Computational Fluid Dynamics (CFD) and flight simulation studies to define and analyze the motion of the airplane, and the physical forces that produce that motion. The *Study* concludes that during the attempted takeoff, the airplane's angle-of-attack (α) exceeded the stall α (α_{stall}) for the combination of flap setting, height above the ground, Mach number, and roll angle (ϕ) present at the time. The stall resulted in a loss of roll control, the contact of the right wing with the ground, and the departure of the airplane off the right side of the runway. The *Study* also concludes that the stall occurred at an α that was below both the in-ground-effect stall α ($\alpha_{stall,IGE}$) predicted by GAC prior to the accident, and the α threshold for the activation of the stick-shaker stall warning (α_{shaker}) in place at the time.

This *Addendum to the Aircraft Performance Study* examines several topics relevant to the field-performance flight-testing during which the accident occurred. Specifically, the *Addendum* considers:

- Whether information about the airplane's aerodynamic performance available at the time of the accident was sufficient to determine that the airplane's actual $\alpha_{stall,IGE}$ was lower than what was assumed.
- How the certification standards for transport category airplanes defined in the FAA Federal Aviation Regulations (FARs)[3] are intended to provide takeoff speed schedules that guarantee safety of flight, including adequate margins from aerodynamic stall.
- The methods used by GAC to generate takeoff speed schedules both before and after the accident.
- The difficulties the test team encountered attempting to capture the takeoff safety speed (V_2) defined in the speed schedules at the time of the accident, and the team's attempts to overcome these difficulties.

The information presented in this *Addendum* indicates that at the time of the accident, the flight test data collected by GAC during previous performance takeoffs of the G650 was sufficient to quantify the changes in lift due to ground-effect. In particular, unexpected wing-

[2] Gulfstream uses the Roman numeral designation "GVI" for aircraft certification purposes and the designation "G650" for marketing purposes. These designations mean the same aircraft model for purposes of this *Addendum* and are used interchangeably.

[3] These standards are specified in 14 Code of Federal Regulations (14 CFR) part 25, and are abbreviated as "FARs" in this *Addendum*.

drop events on two previous takeoffs (which were determined after the accident to also be the result of asymmetric stalls in ground-effect), provided evidence of the actual reduction in α_{stall} due to ground-effect ($\Delta\alpha_{stall,IGE}$). These prior events indicate that the actual $\Delta\alpha_{stall,IGE}$ is greater than the $\Delta\alpha_{stall,IGE}$ estimated on the basis of previous GAC airplane programs and on wind tunnel tests of the G650, and used to determine whether the α_{shaker} threshold was appropriate. The investigation revealed that while the pilot flying during the first of the wing-drop events (who was also the pilot flying on the accident flight) later briefed a limited audience within the flight-test community about the event, the second wing-drop event was not briefed beyond the flight crew involved, and GAC did not perform an analysis to determine the root physical cause of either of the previous wing-drop events until after the accident.

The investigation also revealed that the takeoff speed schedules developed for the field performance tests were built around a decision to make the airplane's takeoff safety speed (V_2) identical to the minimum V_2 allowed by the FARs. As a result, during performance takeoffs the airplane was being operated with smaller margins to stall than on previous GAC airplane programs. At the same time, GAC did not use any dynamic analysis or simulation modeling of the takeoffs prior to field performance flight tests to determine if the scheduled speeds were achievable. Throughout the field performance testing, the airplane consistently "overshot" the desired speeds (i.e., reached 35 ft. AGL at a speed faster than the targeted speed). Following the first round of field performance testing in Roswell in November 2010, test crews attempted, through an iterative approach, to find a takeoff rotation technique that would enable the airplane to capture the desired speeds at 35 ft. AGL. A rotation technique employing an abrupt column pull of over 60 lb. was found to reduce the magnitude of the speed overshoots, though it did not completely solve the problem.

Prior to the accident flight, GAC engineers reduced the flaps 10 target pitch angle for takeoff rotation from 10° to 9° to accommodate abused takeoff requirements, and to provide a consistent pitch angle target for both flaps 10 and flaps 20. However, the flaps 10 takeoff speed schedules were developed for a target pitch angle of 10°, and through an oversight, were not adjusted upwards as necessary following the lowering of the pitch target to 9°. This exacerbated the difficulty in capturing the target speeds for flaps 10 takeoffs. On the day of the accident, the test crew was again exploring takeoff techniques to solve the speed overshoot problem using an iterative approach. In an attempt to keep the speed down, over the course of the morning, the crew used progressively briefer "pauses" at the target pitch angle of 9° before increasing the pitch angle further. On the accident takeoff, there was no pause at 9° at all, but only a slowing of the pitch rate, as the airplane pitched through 9° and then stalled at a pitch angle of approximately 11.2.°

In the time since the accident, GAC has updated its takeoff speed development and testing methods to use simulation and modeling as their foundation. Simulations are used to compute achievable takeoff speeds and ensure that they provide adequate margins to stall throughout the takeoff maneuver; to develop and validate rotation techniques through pilot-in-the-loop simulation; and on-site during field performance testing, to predict airplane performance prior to each run for real-time comparison with actual performance.

This Addendum references various GAC personnel involved in the G650 program, including flight test engineers, aircraft performance engineers, test pilots, and managers. Citations of interviews with these individuals, and the positions they occupied in the G650 engineering and flight test program, are noted throughout the Addendum. For clarity and consistency, these persons are referenced according to the codes listed in Table 1. These codes are identical to those used in the *On Board Video Recording Group Chairman's Factual Report* (Reference 29), with additional codes added as required.

Code	Position / Title
P-1	Pilot-In-Command (PIC) on the accident flight
P-2	Second-In-Command (SIC) on the accident flight
P-3	GAC G650 Project Pilot
P-4	Engineering Test Pilot
FTE-1	Lead Flight Test Engineer for field performance testing during the accident flight
FTE-2	2nd Flight Test Engineer during the accident flight
TM-1	Flight Sciences G650 Airplane Performance Group Head
TM-3	Flight Test Engineering Technical Specialist, Aerodynamics (contracted) during the accident flight
SSAA	Flight Sciences Staff Scientist for Applied Aerodynamics
PE	Flight Sciences Principal Engineer for Airplane Performance

Table 1. Codes for GAC personnel used in this *Addendum*.

D. DETAILS OF THE INVESTIGATION

I. Estimate of lift in ground-effect based on data available as of April 2, 2011

Overview: modeling of lift in ground-effect

As described in the *Aircraft Performance Study* (Reference 1) and summarized above, during the accident takeoff, α exceeded the α_{stall} for the combination of flap setting, height above the ground, Mach number, and roll angle (ϕ) present at the time. Furthermore, the actual $\alpha_{stall,IGE}$ was below both the $\alpha_{stall,IGE}$ used by GAC prior to the accident, and α_{shaker}. It is of interest to determine whether the G650 flight-test data collected prior to the accident would have been sufficient to determine a more accurate estimate of $\alpha_{stall,IGE}$, had such an analysis been attempted. A more accurate estimate of $\alpha_{stall,IGE}$ could have resulted in values of α_{shaker} and / or takeoff speed schedules that provided better protection from an inadvertent stall near the ground.

As mentioned in the *Study*, the qualitative effects of ground-effect are well understood. As stated there, "…the downwash produced by the wing trailing vortices is reduced by the proximity of the ground plane, which in turn reduces the induced angle of attack and induced drag, and increases the C_L at a given α." These effects are sketched in Figure 22 in the *Study*, which is taken from Reference 2 (of this *Addendum*) and included here as Figure 1.

Figure 1 illustrates that the rate of change of lift coefficient (C_L)[4] with α ($\partial C_L/\partial\alpha$) increases in ground-effect, and that ground-effect is most pronounced at the lowest wing heights, and decreases rapidly and non-linearly as height above the ground increases. Based on these observations, the C_L in-ground-effect ($C_{L,IGE}$) can be modeled in terms of the C_L out-of-ground-effect ($C_{L,OGE}$) using a multiplier (k_h) on $C_{L,OGE}$ which is itself a function of height above the ground (h_{CFD}):

$$C_{L,IGE} = \left(\frac{\partial C_L}{\partial \alpha}\right)_{IGE} (\alpha - \alpha_0) \qquad [1]$$

[4] C_L is defined in Equation [22] in the *Study.*

Where

$$\left(\frac{\partial C_L}{\partial \alpha}\right)_{IGE} = k_h \left(\frac{\partial C_L}{\partial \alpha}\right)_{OGE} \qquad [2]$$

And

$$k_h = f(h_{CFD}) \qquad [3]$$

Therefore

$$C_{L,IGE} = k_h \left(\frac{\partial C_L}{\partial \alpha}\right)_{OGE} (\alpha - \alpha_0) \qquad [4]$$

$$C_{L,IGE} = k_h \big(C_{L,OGE}\big) \qquad [5]$$

Where α_0 is the α for C_L = 0, and h_{CFD} is the reference height for the GAC CFD analysis described in the *Study*. Note that since at C_L = 0 the downwash α should also be close to zero, it is reasonable to assume that α_0 is the same in- and out-of-ground-effect.

From Equation [5], if $C_{L,IGE}$ and $C_{L,OGE}$ are known, k_h can be computed:

$$k_h = \frac{C_{L,IGE}}{C_{L,OGE}} \qquad [6]$$

At a given α, $C_{L,OGE}$ is known from the free-air flight tests of the G650, as documented in Reference [3]. The actual $C_{L,IGE}$ developed during a particular takeoff can be computed using the methods used in the simulation aerodynamic coefficient "residual" analysis described in the *Study*. Finally, it is assumed that $k_h \rightarrow 1.0$ as $h_{CFD} \rightarrow b$, where b is the wingspan of the airplane (see Figure 1).

By analyzing a large number of takeoffs, computations of k_h at varying combinations of h_{CFD} and α can be obtained. Fitting a curve through a plot of the resulting k_h vs. h_{CFD}, and forcing $k_h \rightarrow 1.0$ as $h_{CFD} \rightarrow b$, provides the definition of k_h indicated by Equation [6]. This definition can then be used to compute $C_{L,IGE}$ at any combination of h_{CFD} and α, per Equation [4]. The results of this calculation using numerous G650 takeoffs are described below, in sub-section "*Model of G650 lift curve in ground-effect using data available at time of accident*."

Note that this model for $C_{L,IGE}$ does not provide any information about $\alpha_{stall,IGE}$. In addition, as observed in the *Study,* existing research is not conclusive regarding the change in α_{stall} due to ground-effect ($\Delta\alpha_{stall,IGE}$). Figure 1 suggests that the maximum C_L attainable in- and out-of-ground-effect ($C_{Lmax,IGE}$ and $C_{Lmax,OGE}$, respectively) are the same; this idea is also reflected in Reference 4, which states that "the aircraft in ground-effect possesses a similar CLMAX as in-flight, but the absolute AOA for stall has reduced." However, other researchers have documented that C_{Lmax} can decrease in ground-effect. For example, one of the conclusions of Reference 5 is that "with flaps deflected, a decrease in height of the wing above the ground resulted in decreases in maximum lift …" [p. 10]. The *Study* points out that for the G650, "the CFD results also indicate that the C_{Lmax} achievable in-ground-effect is *also* reduced compared to C_{Lmax} out-of-ground-effect," in contrast to the behavior depicted in Figure 1 and noted in Reference 4, but consistent with the conclusions of Reference 5.

The *Study* notes that, regarding the increment in α_{stall} due to ground-effect ($\Delta\alpha_{stall,IGE}$),

> Based on previous GAC airplane programs and on low-speed wind tunnel tests, prior to the accident GAC engineers expected $\Delta\alpha_{stall,IGE}$ to be about -2° (Reference 14, p. 15). At a previous point in the flight test program, one of the flight test engineers on the accident flight adjusted this increment to -1.6° based on an analysis of minimum-unstick speed takeoff (V_{mu}) tests (References 9 and 10; Reference 14, p. 15). [References cited are those in the *Study*, not this *Addendum*].

The flight test engineer's (FTE-1's) analysis of the V_{mu} tests (Reference 10 of the *Study*, and Reference 6 of this *Addendum*) was still in draft form at the time of the accident. However, it appears from this draft document that FTE-1's adjustment to $\Delta\alpha_{stall,IGE}$ based on the V_{mu} tests reflects the assumption sketched in Figure 1 and stated in Reference 4 that "the aircraft in ground-effect possesses a similar CLMAX as in-flight" (i.e., in free-air). The remainder of this Section examines the adjustment to $\Delta\alpha_{stall,IGE}$ based on the V_{mu} tests as gleaned from Reference 6, and considers how a better estimate of $\Delta\alpha_{stall,IGE}$ could have been obtained by an analysis of two previous in-ground-effect roll-off events experienced during field performance testing. The $C_{L,IGE}$ curves obtained by combining the resulting $\alpha_{stall,IGE}$ with the $C_{L,IGE}$ model defined by Equations [3] and [4] are then compared with the $C_{L,IGE}$ curves resulting from the post-accident GAC CFD analysis described in the *Study*.

GAC estimates of $\Delta\alpha_{stall,IGE}$ at the time of the accident

Reference 6 is a draft report of the results of the G650 minimum-unstick speed (V_{mu})[5] tests, prepared by the lead flight test engineer on the accident flight (FTE-1). The *Summary* at the beginning of the report states:

> This flight test report contains Gulfstream GVI company data for minimum unstick speed (V_{MU}) testing. The testing was conducted using GVI S/N 6002 at Roswell International Air Center in Roswell, New Mexico during the Phase I field performance testing from November 8th through the 20th of 2010. V_{MU} testing was conducted on flights 81, 83, 88 and 91 for heavy and light weight forward limit Center of Gravity (CG), flaps 10 and 20, and for All Engines Operative (AEO) minimum gradient and One Engine Inoperative (OEI) simulated minimum gradient testing. Testing was conducted by building up in pitch attitude, down in thrust, and down in weight.

The *Test Results* section of Reference 6 includes a comparison of $C_{L,IGE}$ and $C_{L,OGE}$:

> Cross plots of pitch attitude versus lift coefficient at liftoff for each flap setting are presented in Figures 1 and 2 [sic], for Flaps 10 and 20, respectively. The plots demonstrate for a constant T/W the variation in lift coefficient with increasing pitch attitude. The free-air trim lift curve, for power off and forward CG, is represented by the dashed line, and when compared a shift of ~1.5 degrees in ground effect can be discerned. Also, for the same liftoff pitch attitude a higher lift coefficient at the AEO thrust setting can be seen. No significant difference between the heavy and light weight test points can be distinguished. The trendline is a linear curvefit of the build up test points. The test points where pitch attitude after liftoff wasn't maintained or aborted due to the thrust set too low are included for reference only to show the trend in the data, but are not included in final curve fit.

From the context of the discussion, it is clear that "Figures 1 and 2" actually refer to Figures 2 and 3 of the draft document, which are included here as Figures 2 and 3 of this *Addendum.* The numerical values on the C_L scale are omitted in order to protect the proprietary nature of the data. The "free-air trim lift curve … represented by the dashed line" is apparent in the Figures, as are the "linear curvefit of the build up test points," and the "shift of ~1.5 degrees in ground effect."

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[5] The definition and significance of V_{mu} speeds are discussed in Section D-II under the sub-section titled "*Role of V_{mu} and V_{LO} in the takeoff speed regulations*."

The *Conclusions* section of Reference 6 notes that "trends using all the of the data show increasing lift coefficient with increasing pitch attitude and decreasing V_{MU} speed / stall speed ratio with increasing thrust to weight ratio [T/W]," but does not mention the "shift of ~1.5 degrees in ground effect" noted in the *Test Results* section. Nonetheless, additional information provided by GAC and interviews with other GAC engineers indicated that the 1.5° shift between the curvefit of the V_{mu} test data and the free-air, trim lift curve observed in Figures 2 and 3 was the basis for FTE-1's adjustment of $\Delta\alpha_{stall,IGE}$ to -1.6°.

For example, Reference 7 includes a slide that states "V_{MU} data analysis indicated a ~1.6deg decrement in AOA for in-ground-effect (IGE) decay – Analysis performed by [FTE-1]." Furthermore, GAC's Staff Scientist in Applied Aerodynamics (SSAA) stated in an interview with NTSB investigators that

> [The] 1-1/2 degrees margin was developed by [FTE-1] during V_{MU} testing in November [2010] from what I understand. And what they had done at the time was … they did V_{MU} testing at various attitudes and using that data, he developed an in ground lift curve and from that developed a margin between alpha max free-air and alpha max in-ground-effect, which was around about 1-1/2 to 1.6 degrees [Reference 8, p. 15].

Figure 4 illustrates the model of C_L in-ground-effect defined by Equations [3] and [4]. The increment between the α in-ground-effect and α out-of-ground-effect for a theoretical V_{mu} test point ($\alpha_{Vmu,IGE}$ and $\alpha_{Vmu,OGE}$, respectively) is depicted in the Figure as $\Delta\alpha_{Vmu}$. The actual V_{mu} data shown in Figures 2 and 3 is too sparse, and occurs over too small of an α range, to depict the increase in $\partial C_L/\partial\alpha$ due to ground-effect illustrated in Figure 4. In fact, Figure 24 of the *Study* indicates that the lift curves in- and out-of-ground-effect generated by CFD solutions are nearly parallel above α = 7° (implying that $(\partial C_L/\partial\alpha)_{IGE} \cong (\partial C_L/\partial\alpha)_{OGE}$ in this area), and that the "spread" in the curves occurs mainly at the lower αs, where the difference between $(\partial C_L/\partial\alpha)_{IGE}$ and $(\partial C_L/\partial\alpha)_{OGE}$ is more pronounced. In other words, the lift curve in ground-effect is not really a perfectly straight line, as depicted in Figure 4. Nonetheless, when attempting to construct the in-ground-effect lift curve without the benefit of the CFD solutions (which were not available before the accident), the model illustrated in Figure 4 is appropriate. The Figure indicates that as modeled, $\Delta\alpha_{stall,IGE}$ is larger than the $\Delta\alpha_{Vmu}$ that would be computed using any V_{mu} test point, since the V_{mu} data was collected at a C_L lower than C_{Lmax}.

From the Figure and Equations [1] and [2], for a given C_L, the difference in α between the in-ground-effect and out-of-ground-effect conditions to achieve that C_L is:

$$\Delta\alpha_{IGE} = (\alpha_{IGE} - \alpha_{OGE})_{C_{L,IGE}=C_{L,OGE}=C_L} = \left[\frac{C_L}{(\partial C_L/\partial\alpha)_{IGE}} + \alpha_0\right] - \left[\frac{C_L}{(\partial C_L/\partial\alpha)_{OGE}} + \alpha_0\right] \qquad [7]$$

$$\Delta\alpha_{IGE} = \frac{C_L}{k_h(\partial C_L/\partial\alpha)_{OGE}} - \frac{C_L}{(\partial C_L/\partial\alpha)_{OGE}} = \frac{C_L}{(\partial C_L/\partial\alpha)_{OGE}}\left(\frac{1}{k_h} - 1\right) \qquad [8]$$

Substituting

$$C_{L,OGE} = \left(\frac{\partial C_L}{\partial\alpha}\right)_{OGE}(\alpha_{OGE} - \alpha_0) \qquad [9]$$

for C_L in Equation [8] gives

$$\Delta\alpha_{IGE} = (\alpha_{IGE} - \alpha_{OGE})_{C_{L,IGE}=C_{L,OGE}} = (\alpha_{OGE} - \alpha_0)\left(\frac{1}{k_h} - 1\right) \quad [10]$$

If $C_{Lmax,IGE} = C_{Lmax,OGE}$, then Figure 4 indicates that $\Delta\alpha_{stall,IGE} = \Delta\alpha_1$, where by Equation [10],

$$\Delta\alpha_1 = \left(\alpha_{stall,IGE} - \alpha_{stall,OGE}\right)_{C_{Lmax,IGE}=C_{Lmax,OGE}} = \left(\alpha_{stall,OGE} - \alpha_0\right)\left(\frac{1}{k_h} - 1\right) \quad [11]$$

As will be shown below, the analysis of several G650 takeoffs indicates that with the gear on the ground and fully compressed, $k_h \cong 1.18$. For flaps 10, α_0 = -1.25°, and at the accident conditions, $\alpha_{stall,OGE}$ = 14.7°. Using these values in Equation [11] gives $\Delta\alpha_1$ = -2.4°, which is 0.8° lower than the -1.6° increment used on the basis of the V_{mu} data, and a more conservative estimate of $\Delta\alpha_{stall,IGE}$.

Figure 4 shows that if $C_{Lmax,IGE} < C_{Lmax,OGE}$, then $\alpha_{stall,IGE}$ will be further reduced by $\Delta\alpha_2$, where

$$\Delta\alpha_2 = \frac{C_{Lmax,IGE} - C_{Lmax,OGE}}{(\partial C_L/\partial\alpha)_{IGE}} = \frac{C_{Lmax,IGE} - C_{Lmax,OGE}}{k_h(\partial C_L/\partial\alpha)_{OGE}} \quad [12]$$

If

$$C_{Lmax,IGE} = k_{C_L} C_{Lmax,OGE} \quad [13]$$

Then

$$\Delta\alpha_2 = \frac{C_{Lmax,OGE}(k_{C_L} - 1)}{k_h(\partial C_L/\partial\alpha)_{OGE}} = \frac{(\partial C_L/\partial\alpha)_{OGE}(\alpha_{stall,OGE} - \alpha_0)(k_{C_L} - 1)}{k_h(\partial C_L/\partial\alpha)_{OGE}} = \frac{(\alpha_{stall,OGE} - \alpha_0)(k_{C_L} - 1)}{k_h} \quad [14]$$

This is the case for the G650; the GAC CFD analysis indicates that for flaps 10, k_{C_L}= 0.95, which with the values of k_h, α_0, and $\alpha_{stall,OGE}$ given above, yields $\Delta\alpha_2$ = -0.7°. The total $\Delta\alpha_{stall,IGE}$ when $C_{Lmax,IGE} < C_{Lmax,OGE}$ is therefore

$$\Delta\alpha_{stall,IGE} = \Delta\alpha_1 + \Delta\alpha_2 = \left(\alpha_{stall,OGE} - \alpha_0\right)\left(\frac{k_{C_L}}{k_h} - 1\right) \quad [15]$$

For the G650 at flaps 10, Equation [15] yields $\Delta\alpha_{stall,IGE}$ = -3.1°, which agrees well with the $\Delta\alpha_{stall,IGE}$ of -3.25° resulting from the CFD analysis.

Without the benefit of the CFD analysis, however, it would not necessarily be known that $C_{Lmax,IGE} < C_{Lmax,OGE}$; in fact, based on the information in Figure 1 and Reference 4 (and without awareness of contrary information such as that in Reference 5), it would be reasonable to assume that $C_{Lmax,IGE} = C_{Lmax,OGE}$. In this case, however, the model illustrated in Figure 4 would give $\Delta\alpha_{stall,IGE}$ = -2.4°, which is more conservative than the estimate of -1.6° based on the V_{mu} points alone, and is closer to the -3.25° value predicted by the CFD analysis.[6]

[6] The SSAA told investigators that to determine $\Delta\alpha_{stall,IGE}$ from flight test data, "you would have to have the stall angle of attack [in] free air [and] have established the stall angle of attack in ground-effect and that would be the true delta. So if your data hadn't gone up to aerodynamic stall as you recognized it, then the delta would be less than what it should be" [Reference 8, p. 35].

For obvious safety reasons, the actual value of $\Delta\alpha_{stall,IGE}$ is not *deliberately* tested in flight. However, if during testing the airplane *inadvertently* encounters stall while in ground-effect, the resulting recorded data is a valuable source of information regarding $\Delta\alpha_{stall,IGE}$. The accident flight experienced such an inadvertent in-ground-effect stall. Similar inadvertent stalls in ground-effect had occurred twice before during field performance testing with N652GD, though these did not result in an accident or damage to the airplane. However, prior to the accident the data from these flights was not analyzed to determine actual values of $\Delta\alpha_{stall,IGE}$.

$\Delta\alpha_{stall,IGE}$ indicated by previous in-ground-effect stalls on N652GD

Prior to the accident flight, N652GD experienced two uncommanded roll events shortly after rotation during field performance tests at Roswell. Flight data from these events are compared with the data from the accident flight in Appendix A.

Flight 88, Run 2A, flown on November 16, 2010, was a flaps 20, light-weight, all-engines-operating (AEO) V_{mu} test, using a reduced symmetric power setting to replicate a desired thrust/weight ratio [References 9 and 10]. Reference 6 (the draft V_{mu} report prepared by FTE-1) describes the roll-off event on this run as follows:

> Flight 88, was flown in the light weight band, to repeat the previous flaps 20 AEO EPR [Engine Pressure Ratio] test. Test point 93-311.05, run 2A, was repeated at an AEO EPR setting and a pitch attitude target of 9° to 10°. The new pilot was unprepared for the aircraft pitch up with full aft stick. The aircraft was rotated to 13° of pitch attitude; 3° beyond the target. The aircraft lifted off around 10° pitch, rolled to the right 8° and 3° back to the left, at which time the pilot called for power while simultaneously pushing the nose down.[7] The TSHA [Test Safety Hazard Analysis] recovery maneuver had been briefed and was flown correctly. … The V_{MU} TSHA and all other build up testing TSHAs were updated to ensure the opportunity to perform a build up was provide[d] to the pilot flying for all tests [p. 17].

The pilot flying (PF) during this event (P-1) was the same PF on the accident takeoff. The pilot included a description and video of this event during a briefing to GAC Flight Operations on November 29, 2010, summarizing the Roswell I Field Performance testing (Reference 10)[8]. A slide in the presentation titled "GVI Roswell Phase I – TSHA-000083 Rev A" stated

> 9. VMU testing will be approached in a build-up manner. Testing will begin at AEO high T/W conditions and proceed to the lower T/W conditions as required. The number of required build-ups and repeat testing will be determined by the on-site test team. *Additionally, the pilot flying shall have recent experience with the test maneuver or perform a build-up maneuver(s) before conducting the test condition* [Reference 10, slide 7; emphasis in original].

The emphasized text on this slide indicates the revision to the V_{mu} TSHA (TSHA-000083) that was developed as a result of the flight 88 event. While GAC updated this TSHA, and Reference 10 contained a schematic of a C_L vs. α curve highlighting various points relevant to the stall warning system, the company did not analyze the flight 88 data itself to determine a value for $\Delta\alpha_{stall,IGE}$.

Flight 132, Run 3B1, flown on March 14, 2011, was a flaps 20, light-weight, one-engine-inoperative (OEI) continued-takeoff (CTO) maneuver. Due to a Flight Control Computer (FCC)

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[7] The plots in Appendix A indicate that at the peak θ of ≈13°, the PF had relaxed his column pull to ≈23 lb. when the PM pushed on the column with ≈21 lb. of force. The PF initially reacted this input with ≈39 lb. of pull, before pushing on the column with ≈4 lb. of force. The resulting column motion was from ≈3° aft to about neutral.

[8] Field performance tests at KROW were conducted in two phases: "Roswell I," from November 8-20, 2010, and "Roswell II," starting on March 6, 2011 (the accident occurred on April 2, 2011).

issue, the yaw damper was selected off for this flight. P-4 was the PIC for this flight, but was in the right seat, and was the pilot monitoring (PM). P-2, the SIC, was in the left seat, and was the PF (P-2 was also the SIC and PM on the accident flight). As shown in the plots in Appendix A, about 0.5 seconds after liftoff, as the pitch angle reached 12°, the roll rate reached 5 deg./sec. to the right. At the same time, the control wheel moved 55° left and the column moved forward of neutral.[9] 1.5 seconds after liftoff, the airplane reached a roll angle of 8° right, the pitch rate was negative, and the pitch angle decreased back through 9°. About 2 seconds after liftoff, the roll rate had reversed back towards the left. About 3 seconds after liftoff, the right throttle was advanced to take-off power to match the left throttle, and the roll angle had decreased to 2° right. The airplane continued the takeoff without contacting the runway.

The actions taken by GAC following this event are described in Reference 11. Some bullet items listed in this document are as follows:

- Rotation was initiated prior to "Rotate" call
  - Rotated at V1 instead of Vr[10]

- Real-time comment by Copilot: "Way High, Way Early"
  - Referring to Pitch attitude and speed at rotation

- Test-day review of event data yielded decision to discontinue Takeoff Performance testing until [yaw damper] was available [Reference 11, slide 4]

Reference 11 also notes that on March 24, 2011 (10 days after the flight 132 event), a meeting was held "to discuss Alpha Limiter and stall warning (shaker) functionality and set up for Takeoff Performance Testing." Video of the flight 132 roll-off event was reviewed at the meeting. A decision was made at this meeting to *increase* the value of α_{shaker} from 85% Normalized Angle of Attack (NAOA) to 90% NAOA, until 10 ft. AGL. Reference 11 notes that "based on data available (Vmu CL primarily), this would provide ~1deg margin to In Ground Effect (IGE) stall angles" [slide 5].

The G650 High Incidence Protection Function (HIPF) is programmed in terms of NAOA, which is a measure of the "usable" α range, and is defined as

$$NAOA = \frac{\alpha - \alpha_0}{\alpha_{SR} - \alpha_0} \qquad [16]$$

Where α_{SR} is the reference $\alpha_{stall,OGE}$, which was set to 0.84° below[11] the actual $\alpha_{stall,OGE}$. Consequently, an increase of α_{shaker} from 85% NAOA to 90% NAOA is equivalent to an α increase from 11.6° to 12.3° at the flaps 10 setting and Mach number of the accident (the absolute value of α_{shaker} for the flaps 20 setting of flights 88 and 132 would be different, though the values of NAOA would be the same). For the accident flight, $\alpha_{stall,OGE}$ = 14.7°, so using the -1.6° $\Delta\alpha_{stall,IGE}$ cited in Reference 7 makes the predicted $\alpha_{stall,IGE}$ = 13.1°. Thus, the α_{shaker} set to 90% NAOA (12.3°) provided a 0.8° margin to the $\alpha_{stall,IGE}$ assumed at the time, but did not provide any warning for the actual stall on the accident flight, which occurred at approximately α = 11.2°.

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[9] The recorded column force data indicates that the column was pushed forward by the PM, not the PF.
[10] The scheduled V_1 and V_R for this run were 110 kts. and 112 kts., respectively. The actual V_R was 109 kts..
[11] The 0.84° margin to $\alpha_{stall,OGE}$ was based on a 0.5° safety margin, and a 0.34° allowance for ADSP tolerances.

Reference 11 notes that during the roll-off event takeoff on flight 132, “rotation was initiated prior to ‘Rotate’ call – rotated at V1 instead of Vr ,” and that P-4[12] commented at the time that the pitch attitude and speed at rotation were “way high, way early.” However, regarding the cause of the roll-off on flight 132, Reference 11 states that “[the] takeaway was that the rolloff was caused by a lateral-directional disturbance (Cl-beta, roll due to sideslip) aggravated by the unavailability of the Yaw Damper.” In particular, an in-ground-effect stall was ruled out, because α did not reach the predicted value for $\alpha_{stall,IGE}$: “Because normalized alpha stayed at or below 0.86 NAOA, this was not determined to be a stall event” [slide 7].

In an interview with NTSB investigators, P-4 (the PIC and PM on flight 132) stated that following the roll event on that flight,

> We talked about it initially. During the brief, during the flight we talked about it but after the flight, [FTE-1][13] and I sat down and talked about it, looked at the data in a cursory manner and I guess the conclusion was that he thought it was a stall but as we looked at the data, he said, look, the stall is at 13 degrees, and these are approximate numbers, and we were at 11½, so it's not a stall. We had over 300 stalls in this airplane, aerodynamic stalls at various altitudes and we've been able to predict it within like a tenth of a degree, very, very close. They say it's going to stall at 14½ or 14 degrees, in that half degree, and that's where that thing would stall based on the data.
>
> So it never occurred to me that the stall angle would be incorrect. And I said to him, I said, look … we spent hundreds of thousands of dollars to put instrumentation in these airplanes and it says it's going to stall at 13, we're at 11.5. We had the yaw damper off, we pulled the right engine to idle, we have a CL Beta potential on this airplane, the airplane rolled in the direction that it would roll with the yaw on the right, to me. We didn't hit the stall angle of attack. It appears to me that that is a CL Beta due to doing this testing with the yaw damper off. Consequently, we're not going to do any more testing until we get the yaw damper fixed or approval to use the yaw damper. And that's where it stood when I left …[14]
>
> … Further evaluation, I guess, was done here. I don't know what it was … I mean, it was reviewed and looked at by more people and I'm not sure of the extent of that. I've just heard anecdotally people say, yes, we looked at that. Yes, we reviewed it. Yes, we saw it. [Reference 12, pp. 5-6].

P-4 was asked whether, after his discussions with FTE-1, he was left with the impression that additional engineering analysis of the roll-off event on flight 132 would be conducted. He answered that

> Yes, I mean, that's why we stopped doing it until it was evaluated or until we could get the yaw damper back on. They are very good at that and either it was said or I assumed that they're going to evaluate it because they do. They look at these things in some detail after the events occur. Some get more attention than others. [Reference 12, p. 9].

Reference 11 notes that, regarding an engineering analysis of this event,

> [FTE-1] requested Flight Sciences/Control Laws group to analyze event w.r.t. planned alpha-limiter system performance to determine if function/system would have had an impact on the test
>
> > – Primary question was whether KCAS-dot and AOA-dot terms being added to a future version would have had an impact given the dynamics of the maneuver [Reference 11, slide 5].

[12] As noted above, P-4 was both PIC and PM on this flight.
[13] FTE-1 was also on board N652GD during the roll-off event on flight 88 (and the accident flight).
[14] The conversation between P-4, P-2, and FTE-1 in the cockpit immediately following the roll-off event on flight 132 (as recorded by on-board video) is discussed below, in Section D-III, subsection “*Takeoff technique adjustments to achieve target V_2/V_{SR} of 1.13.*” This conversation reflects a concern with stalling the airplane, more than a concern with lateral / directional disturbances associated with the unavailability of the damper.

The results of this analysis were provided to FTE-1 on March 29, 2011 (5 days after the March 24 meeting, and 4 days before the accident). The results indicated "that AOA-limiting would not have activated because the AOA and rate terms never got high enough to trigger the onset with weight off wheels" [Reference 11, slide 6]. Reference 11 notes that

> Following the FLT132 review, [FTE-1] then requested the same review of the FLT088 Vmu test rolloff event (3/30/2011)
>
> – In the email distributing the results of the FLT132 review, [FTE-1] stated of the FLT088 review that "Hopefully, it will show the limiter catching us before we got to the 13 deg pitch attitude. If not it should."
>
> – Analysis never completed because original request cited wrong flight number

In addition to these requests by FTE-1 concerning the expected behavior of the (yet to be implemented) HIPF system during the roll-off events on flights 88 and 132, reports of the conversation between FTE-1 and P-1 during the pre-flight briefings for flight 153 (the accident flight) suggest that the potential for an in-ground-effect stall at pitch angles approaching 13° was discussed. Reference 14 is an internal GAC memorandum from the performance group technical lead on-site for flight 153 (TM-1), containing notes of the pre-flight briefing for flight 153. As stated there,

> The purpose of Flight 153 was to perform heavyweight continued takeoffs, and as time permitted to proceed to medium weight CTOs. The takeoff testing was intended to be to practice the small revisions that were made to the takeoff technique to ensure that it was repeatable. .... The takeoff pitch angle to target was 9 degrees for flaps 20 or flaps 10 takeoffs, realizing that there is a tolerance of +/- 1 degree. This target was agreed upon by [FTE-1], [the PE], and Chief FTE Staff Scientist, and myself. Further discussion of this target included [FTE-1] and [P-1] reflecting on a previous pitch overshoot during V_{MU} testing, saying comments like "we've already been there, we don't want to go there again" and indicating that if they saw 11 or 12 degrees, it was a knock-it-off and recover maneuver. [P-1] was particularly concerned about the pitch overshoot, saying that he "didn't like it."

These notes do not indicate whether FTE-1 or P-1 ever used the term "stall" in this discussion, and so it is not known whether they specifically associated a stall with the dangers of a "pitch overshoot." However, it would be natural to make this association; for example, the GAC Chief Flight Test Engineer told NTSB investigators that "[flight] 88 was, if I remember correctly, early rotation and an over rotation and the pitch went up into stall" (Reference 15, p. 44). Similarly, the GAC SSAA stated to NTSB investigators, "over-rotation of the aircraft in my mind leads to a stall" (Reference 8, p. 34).[15] In any event, the discussion reported by TM-1 indicates that FTE-1 and P-1 associated the danger inherent in a "pitch overshoot" with pitch angles approaching 13°. The *Study* indicates that the stall on flight 153 occurred as the pitch angle was increasing through 11.2°, and as described below, an analysis of the root physical causes of the roll-off events on flights 88 and 132 would have revealed that during these flights, the airplane stalled at angles of attack measurably below 13°.

After the accident on flight 153, GAC performed simulation "residual" and CFD analyses of the roll-off events on flights 88 and 132, similar to the analyses performed for the accident flight and described in the *Study*. The results of these analyses indicate that the cause of the roll-offs on flights 88 and 132 was the same as the cause of the uncontrolled rolling moment on the accident flight: a stall of the outboard right wing, at a lower-than-expected α. In particular,

[15] Other examples of the association of a "pitch overshoot" (over-rotation) with stall are provided by Test Hazard Assessments #94 and #95 (Document Number 25.107, *Takeoff Speeds*) included in the NASA Flight Test Safety Database (see http://ftsdb.grc.nasa.gov). These list one of the hazards of V_{mu} and OEI testing as "aircraft departs runway / inadvertent ground contact," caused by, among other things, "excessive rotation force / over-rotation at low speed, low altitude stall."

the residual analysis indicates that the stalls occurred at about α = 11.6° on flight 88 and about α = 11.0° on flight 132,[16] and the CFD analysis predicts that at flaps 20 with the gear on the ground and fully compressed, $\alpha_{stall,IGE}$ = 11.2°, corresponding to a $\Delta\alpha_{stall,IGE}$ of -3.0°.[17] As the GAC Director of Flight Sciences for the G650 program explained to NTSB investigators, "… based on [the] residual analysis, … there was a divergence that occurred on 88 and 132, similar to what happened on Flight 153, and there was a right-hand tip stall" [Reference 13, p. 47].

Model of G650 lift curve in ground-effect using data available at time of accident

Figure 5 shows the results of the k_h calculation defined by Equation [6] using the flaps 10 takeoffs identified in Reference 6. Though there is considerable scatter in the data, the trends clearly show the basic non-linear decrease of ground-effect with altitude, as sketched in Figure 1. In Figure 5, the data has been "corrected" as necessary to force $k_h \rightarrow 1.0$ as $h_{MG}/b \rightarrow 1.0$. h_{MG} is the height of the fully-extended main gear above the ground; it is related to the h_{CFD} used in the GAC CFD calculations (described in the *Study*) as follows:

$$h_{MG} = h_{CFD} - 6.97\,ft. \qquad [17]$$

As described above, in the absence of better information (such as the CFD results), the C_L vs. α curve in ground-effect at any given h_{CFD} can be approximated by multiplying the C_L values of the free-air C_L vs. α curve by the value of k_h from Figure 5 corresponding to the h_{CFD} of interest (Equation 5). The result will reflect the change in the slope of the C_L vs. α curve due to ground-effect, but it will not reflect the reduction in α_{stall} due to ground-effect ($\Delta\alpha_{stall,IGE}$). To estimate $\Delta\alpha_{stall,IGE}$ at any given h_{CFD}, a value of $\Delta\alpha_{stall,IGE}$ gleaned from the roll-off events on flights 88 and 132 can be used.

The free-air, flaps 20 α_{stall} is 14.2° (at the accident Mach number); consequently, the $\Delta\alpha_{stall,IGE}$ indicated by the roll-off on flight 88 is 11.6° - 14.2° = -2.6°, and the $\Delta\alpha_{stall,IGE}$ indicated by the roll-off on flight 132 is 11.0° - 14.2° = -3.2°. These events occurred at slightly different values of h_{CFD}, and it is apparent that $\Delta\alpha_{stall,IGE} \rightarrow 0$ as $h_{CFD}/b \rightarrow 1$; consequently, a method for estimating $\Delta\alpha_{stall,IGE}$ as a function of h_{CFD}, accounting for the values of $\Delta\alpha_{stall,IGE}$ evident in flights 88 and 132, is required.

The k_h plotted in Figure 5 indicates how the ground-effects decay with increasing h_{CFD}/b. It is reasonable to assume that $\Delta\alpha_{stall,IGE}$ will decay in a similar manner:

$$\Delta\alpha_{stall,IGE} = c_h\left(\Delta\alpha_{stall,IGE}\right)_{max} \qquad [18]$$

$$c_h = f(h_{CFD}/b) \qquad [19]$$

$\left(\Delta\alpha_{stall,IGE}\right)_{max}$ is the maximum possible value of $\Delta\alpha_{stall,IGE}$, i.e., the value of $\Delta\alpha_{stall,IGE}$ at the lowest possible h_{CFD}. c_h is a multiplier that is equal to 1.0 at the lowest possible h_{CFD} and equal to 0.0 in free air, and that has a dependence on h_{CFD}/b that is similar to that of k_h plotted in Figure 5. To construct c_h, k_h can be written

[16] These values of α have been corrected for pitch rate effects on the recorded α, as described in the *Study*.
[17] A $\Delta\alpha_{stall,IGE}$ of -3.0° at liftoff is conservative, since the gear is never fully compressed at this point.

$$k_h = 1.0 + \Delta k_h = 1.0 + c_h(\Delta k_h)_{max} \quad [20]$$

$$(\Delta k_h)_{max} = (k_h)_{max} - 1.0 \quad [21]$$

$$c_h = \frac{k_h - 1.0}{(k_h)_{max} - 1.0} \quad [22]$$

Where $(k_h)_{max}$ is the value of k_h plotted Figure 5 evaluated at the lowest possible h_{CFD}.

Using the values of $\Delta\alpha_{stall,IGE}$ from flights 88 and 132, and the values of c_h at which the stalls on these flights occurred, estimates of $(\Delta\alpha_{stall,IGE})_{max}$ of -3.1° and -3.9° are obtained from flights 88 and 132, respectively.[18] For constructing the model of lift in ground-effect, these estimates are averaged, and a value of $(\Delta\alpha_{stall,IGE})_{max}$ of -3.5° is assumed.

Figure 6 presents several C_L vs. α curves in ground-effect[19] constructed using:

- The flaps 10 free-air lift curve from the CFD solution
- The free-air flaps 10 α_{stall} = 14.7° (at the accident Mach number)
- Equations [5], [18], and [22]
- $k_h = f(h_{CFD}/b)$, as plotted in Figure 5
- $(\Delta\alpha_{stall,IGE})_{max}$ = -3.5°, based on the roll-off events on flights 88 and 132[20]
- h_{CFD}/b values corresponding to the compressed main gear at 0, 35, 70, and 130 inches off the ground

The values of h_{CFD}/b for the curves presented in Figure 6 are those corresponding to the GAC CFD solutions plotted in Figure 24 of the *Study*. These same solutions are also plotted in Figure 6 (of this *Addendum*) for comparison with the C_L vs. α curves constructed using the k_h ground-effect model. Note that though the free-air CFD solution was used in the model, this CFD solution is in excellent agreement with flight test data, and so equivalent results can be obtained using the flight-test derived flaps 10 free-air C_L vs. α curve (which was available prior to the accident).

Figure 6 shows that the k_h model preserves the shape of the free-air lift curve (as expected), and so the "rounding" of the curve in ground-effect depicted by the CFD solutions is not reflected in the model-based curves. Moreover, the model over-estimates $\Delta\alpha_{stall,IGE}$ by about -0.5°. Nonetheless, the results in Figure 6 show that a reasonable, if somewhat conservative, estimate of the C_L vs. α curve and of $\Delta\alpha_{stall,IGE}$ can be obtained using the k_h model, which is built using information that was available before the accident. Consequently, the results in Figure 6 show that a better estimate of the G650's ground-effect characteristics could have been obtained through an analysis of the takeoff data available at the time of the accident, and of the roll-off events on flights 88 and 132 in particular.

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[18] These calculations assume $\alpha_{stall,OGE}$ = 14.2°, $\alpha_{stall,F88}$ = 11.6°, $\alpha_{stall,F132}$ = 11.0°, and h_{CFD}/b = 0.0842 and 0.08292 at the stall points on flights 88 and 132, respectively. Mach and sideslip effects on $\alpha_{stall,OGE}$ are ignored.

[19] To protect the proprietary nature of the data, the numerical values have been removed from the C_L axis in Figure 6, and only data for α ≥ 8° is shown.

[20] It is assumed that this value of $(\Delta\alpha_{stall,IGE})_{max}$ applies to both flaps 10 and flaps 20.

GAC analyses of roll-off events on previous airplane flight-test programs

The analysis outlined above addresses whether or not a better estimate of ground-effects on the G650 using data available before the accident was *possible*. A separate question is whether it would have been *reasonable* for the GAC program team to have undertaken such an analysis prior to the accident. The roll-off events on flights 88 and 132 provide crucial information about $\Delta\alpha_{stall,IGE}$, and while several actions were taken by the flight test team in response to these events, these did not include an analysis to determine $\Delta\alpha_{stall,IGE}$. In hindsight, the absence of such an analysis seems unusual; and in fact, GAC's responses to roll-off events during takeoffs on previous airplane flight-test programs provide precedents for an analysis of $\Delta\alpha_{stall,IGE}$ following such events.

Reference 16 documents two roll-off events during takeoff performance testing of the GIV airplane, that are very similar to the roll events on N652GD flights 88, 132, and 153:

> During the take-off performance testing of the Gulfstream IV, two instances of aerodynamic stall before pusher actuation were experienced in close proximity to the ground. Each occurred during abusive minimum unstick speed (Vmu) testing, where the aircraft was rotated aggressively during take-off in the attempt to get it airborne at a minimum airspeed. In one of these maneuvers, the aircraft rolled sharply, striking its right wing tip on the runway. A review of the records showed the pusher system to be working normally; the stall in ground effect was occurring two degrees lower angle of attack than in free air.

Reference 16 goes on to describe the airflow separation pattern on the GIV wing, and the "development of the Gulfstream IV stall improvement package focused on slowing both the chordwise and spanwise spread of the airflow separation during the progress of the stall." Clearly, the underlying physical causes of the roll events on the GIV were thoroughly analyzed, and in particular, $\Delta\alpha_{stall,IGE}$ was determined to be -2°.

An unexpected roll-off event during takeoff performance testing also occurred on the GV airplane. This event was analyzed in two GAC Flight Test reports (References 17 and 18). Reference 17 describes the event as follows:

> An unusual event occurred during the course of field performance testing for alternate takeoff and landing configurations at Roswell, New Mexico in June 1997. Immediately after liftoff, while performing Minimum Unstick Speed (VMU) testing for Flaps 10°, the test airplane (GV SIN 503) rolled to the right (in excess of 20°) before the airplane could be brought back to wings level. The subsequent recovery resulted in a hard landing but no major damage was experienced. The event was initially described by the flight crew as an aerodynamic stall immediately after liftoff.
>
> This report presents an analysis of that maneuver; GV SIN 503, Flight 297, Run 13. Review of the data available, shows that this was not an aerodynamic stall and that the roll rates and attitudes achieved during the maneuver were caused primarily by a direct crosswind from the left at very low (stall barrier actuation) airspeed [p. 1].

Reference 17 also describes an analysis of the roll performance of the airplane that is analogous to the simulation "residual" analysis used by GAC to analyze N652GD flights 88, 132, and 153 after the accident:

> The response to roll command had also been described as sluggish. A theoretical analysis using a computer model has been performed in order to understand the effects of control input and crosswind component on rolling characteristics. The results of this analysis are presented in Figures 9 and 10 .... Examination of Figure 9 shows that throughout the majority of the maneuver, the overriding contributor to rolling moment is airframe reaction to the crosswind and that the control surface deflection is only a

> minor contributor. Correlating Figure 9 with Figure 2, it can also be seen that the total rolling moment is not reversed until nearly full lateral control is input. This would give the impression of sluggish response. However, when full lateral control is finally achieved, the roll rate has been reversed and the airplane begins to roll wings level.
>
> Figure 10 provides an estimate of roll rate generated by the computer model compared to that experienced during the maneuver. Since the model is not constrained by landing gear, it shows a roll rate even while the airplane is on the ground. Once the airplane lifts off however, the model shows good agreement with the flight test roll rates [pp. 5-6; Figures referenced are those in Reference 17].

The detail of analysis presented in References 16, 17, and 18 suggests that had similar attention been given to the roll-off events on N652GD flights 88 and 132, better knowledge about the true value of $\Delta\alpha_{stall,IGE}$ on the G650 could have been obtained prior to the accident.

II. Takeoff speeds regulations in 14 CFR Part 25

Overview

The α required for an airplane to lift off during takeoff is primarily dependent on the airplane's weight, configuration (flap setting, stabilizer trim, etc.), and speed. Clearly, if takeoff rotation had been initiated at a higher speed during the accident flight, then the airplane could have lifted off the runway at a lower α, and with a larger α margin from stall. Consequently, understanding the takeoff speeds in use during the accident flight can help illuminate why the crew pitched the airplane to high pitch (θ) and α angles, even though TM-1 reported that FTE-1 and P-1 had agreed that "if they saw 11 or 12 degrees, it was a knock-it-off and recover maneuver."

The takeoff speed schedules used by the flight crew were provided by the Performance Group within the GAC G650 Flight Sciences organization, and consisted of tabulated values of the decision speed (V_1), rotation speed (V_R), and takeoff safety speed (V_2) as a function of flap setting and aircraft gross weight. The Performance Group developed these speed schedules based on the free-air stall speeds of the airplane as determined by flight-test, and on the takeoff speed requirements specified in the Federal Aviation Regulations (FARs) for Transport Category Airplanes (14 Code of Federal Regulations (CFR) Part 25).

The takeoff speeds most relevant to this accident are V_R and V_2. The *Study* notes that regarding the accident takeoff maneuver,

> The procedure for conducting the takeoff is specified in a "test card" for the OEI, CTO maneuver ... In this procedure, the airplane is aligned with the runway centerline and the brakes are applied. The engine power is set to the desired level, and then the brakes are released. At a specified speed (105 knots in this case), the right throttle is reduced to idle to simulate a failure of the right engine; the speed is selected so as to allow time for the engine power to reduce to idle by the rotation speed. At the rotation speed (127 knots in this case), the column is pulled with a specified force (60-65 lb. in this case) to initiate rotation; the pull is then relaxed to "gradually capture [9°] pitch attitude."[21]
>
> The procedure is then to "maintain target pitch attitude until V_2 [the takeoff safety speed] is achieved, then transition to speed." The landing gear is retracted after a positive rate-of-climb is established, and the pitch attitude is adjusted to maintain V_2 until the gear retraction is complete, or until the airplane

[21] The test card for the accident run specified a pitch target of 10°, but this target was reduced to 9° prior to the accident flight and was briefed during pre-flight briefings (see discussion in Reference 1 of the *Study*).

climbs through 400 ft. above ground level (AGL) (whichever occurs first), at which point the maneuver is complete.

As will be discussed further, during the field performance testing of the G650 the test team had experienced difficulties with “overshooting” the target speeds; i.e., the pilots had difficulty in stabilizing the airplane in an initial climb at the target speed, without first accelerating to a speed faster than the target during rotation and liftoff. Generally, the target speeds were V2 + 10 knots for AEO takeoffs, and V_2 for OEI takeoffs. For simplicity, hereafter any overshoot of the target speed (for both V_2 and V_2 + 10 knots) will be referred to as a “V_2 overshoot”. The takeoff immediately preceding the accident takeoff was for a similar condition as the accident (flaps 10 OEI), and overshot V_2 by 9 knots. Discussions among the crew recorded by on-board video indicate that on the accident takeoff, P-1 intended to rotate the airplane to a higher θ, and even, if necessary, beyond the target θ of 9° specified on the test card, in order to reduce the magnitude of V_2 overshoot experienced on the previous takeoff.

The definitions of and relationships between the takeoff speeds specified in the FARs are intended to provide takeoff speed schedules that guarantee safety of flight, including adequate airplane control in the event of an engine failure, and a safe margin from aerodynamic stall. To understand how these safety goals are achieved, and how the takeoff speed schedules for the G650 field performance testing were developed, it is useful to review the definitions and requirements in FARs 25.103 and 25.107. In particular, the definition of V_2 and V_R, which in turn rest on the definitions of stall speed and the minimum-unstick speed (V_{mu}), are of interest.

The requirements for the takeoff rotation speed (V_R) are intended to ensure:

- An opportunity to abort the takeoff at or before the takeoff decision speed (V_1), without having the airplane committed to flight (i.e., rotated for takeoff) (§25.107(e)(1)(i))[22]
- Adequate lateral/directional control in the event of an engine failure (§25.107(e)(1)(ii))
- Reaching the takeoff safety speed (V_2) prior to an altitude of 35 ft. AGL (§25.107(c)(2), §25.107(e)(1)(iii))
- A safe speed margin from stall during rotation and liftoff, even for over-rotation or out-of-trim conditions (§25.107(e)(1)(iv), §25.107(e)(2), §25.107(e)(4))
- No marked increase in the Airplane Flight Manual (AFM) takeoff field length in the event of an engine failure when the airplane is rotated 5 knots early (§25.107(e)(3))
- No marked increase in the AFM takeoff filed length or unsafe characteristics during abused takeoffs in which rotation is early, fast, and high (§25.107(e)(4))

The requirements for the takeoff safety speed (V_2) are intended to ensure:

- A safe speed margin from stall during rotation and climb-out, including maneuvering requirements (§25.107(c)(1), §25.107(b)(1)(ii), §25.107(c)(3))
- Adequate lateral/directional control in the event of an engine failure (§25.107(c)(1), §25.107(b)(3))
- A safe minimum climb gradient in the event of an engine failure (§25.107(c))

In these requirements, the safety margins from stall are obtained by specifying minimum ratios of V_R to the demonstrated minimum control (V_{MC}) and V_{mu} speeds, and of V_2 to a

[22] In this discussion, the § symbol will be used denote paragraphs of the FARs.

reference speed. Consequently, the stall margin at the minimum allowable value of V_2 (V_{2min}) will depend on the value of the reference speed, and on the factor to be applied to the reference speed to obtain V_{2min}. The definition of the reference speed, and the factor to be applied to this speed to obtain V_{2min}, changed in November 2002, between the FAA certification of the GV airplane in April 1997, and the establishment of the certification basis for the GVI in March, 2007. As discussed further below, this change is one factor that contributed to reduced stall margins for field performance development work on the G650, compared to previous GAC models. To understand this contribution, the change in the definition of the reference speed and the associated safety factors needs to be reviewed.

Stall speed definition in FAR 25.103

Prior to Amendment 25-108 (November 26, 2002)[23] of the FARs, the reference speed upon which other speeds (such as V_2) were based was the "stalling speed" (V_S), which is the minimum speed demonstrated in the stalling maneuver. Reference 19 states that V_S "can be less than the lowest speed at which the airplane's weight is still supported entirely by aerodynamic lift," which led to concern that the speed margins from stall based on V_S may be less than intended. To address this concern, Amendment 25-108 changed the reference speed to the "1-g stall speed," which is the "minimum speed for which the lift provided by the wing is capable of supporting the weight of the airplane." As stated in Reference 19,

> … the stalling speed (V_S) is defined as the minimum speed demonstrated in the performance stall maneuver described in § 25.103 of 14 CFR part 25 (part 25). V_S has historically served as a reference speed for determining the minimum operating speeds required under part 25 for transport category airplanes.
>
> Examples of minimum operating speeds that are based on V_S include the takeoff safety speed (V_2), the final takeoff climb speed, and the landing approach speed. For example, under part 25, V_2 must be at least 1.2 times V_S, the final takeoff climb speed must be at least 1.25 times V_S, and the landing approach speed must be at least 1.3 times V_S.
>
> The speed margin, or difference in speed, between V_S and each minimum operating speed provides a safety ''cushion'' to ensure that normal operating speeds are sufficiently higher than the speed at which the airplane stalls. Using multiplying factors applied to V_S to provide this speed margin, however, assumes that V_S provides a proper reference stall speed. Since V_S is the minimum speed obtained in the stalling maneuver, it can be less than the lowest speed at which the airplane's weight is still supported entirely by aerodynamic lift. If V_S is significantly less than this speed, applying multiplying factors to V_S to determine the minimum operating speeds may not provide as large a speed margin as intended.
>
> A proper reference stall speed should provide a reasonably consistent approximation of the wing's maximum usable lift. Maximum usable lift occurs at the minimum speed for which the lift provided by the wing is capable of supporting the weight of the airplane. This speed is known as the 1-g stall speed because the load factor (the ratio of airplane lift to weight) at this speed is equal to 1.0 ''g'' (where ''g'' is the acceleration caused by the force of gravity) in the direction perpendicular to the flight path of the airplane. Speeds lower than the 1-g stall speed during the stalling maneuver represent a transient flight condition that, if used as a reference for the deriving minimum operating speeds, may not provide the desired speed margin to protect against inadvertently stalling the airplane.
>
> For transport category airplanes, the minimum speed obtained in the stall maneuver of § 25.103 usually occurs near the point in the maneuver where the airplane spontaneously pitches nose-down or where the pilot initiates recovery after reaching a deterrent level of buffet, i.e., a vibration of a magnitude and severity that is a strong and effective deterrent to further speed reduction. Early generation transport category airplanes, which had fairly straight wings and non-advanced airfoils, typically pitched nose-

[23] See Reference 19.

> down near the 1-g stall speed. The minimum speed in the maneuver was easy to note and record, and served as an adequate approximation of the speed for maximum lift.
>
> For the recent generation of high speed transport category airplanes with swept wings and highly advanced airfoils, however, the minimum speed obtained in the stalling maneuver can be substantially lower than the speed for maximum lift. Furthermore, the point at which the airplane pitches nose down or exhibits a deterrent level of buffet is more difficult to distinguish and can vary with piloting technique. As a result, the minimum speed in the stalling maneuver has become an inappropriate reference for most modern high speed transport category airplanes for establishing minimum operating speeds since it may: (1) Be inconsistently determined, and (2) represent a flight condition in which the load factor perpendicular to the flight path is substantially less than 1.0 g.

Reference 19 goes on to describe how the use of the same multiplying factors that were used to define operational speeds using a reference speed based on V_S were not appropriate for defining those speeds using a reference speed based on the 1-g stall speed (V_{S1g}), for airplanes that incorporate flight control systems that afford flight envelope protection, including protection from stall:

> In recent years, advanced technology transport category airplanes have been developed that employ novel flight control systems. These flight control systems incorporate unique protection features that are intended to prevent the airplane from stalling. They also prevent the airplane from maintaining speeds that are slower than a small percentage above the 1-g stall speed. Because of their unique design features, the traditional method of establishing V_S as the minimum speed obtained in the stalling maneuver was inappropriate for these airplanes. The FAA issued special conditions for these airplanes to define the reference stall speed as not less than the 1-g stall speed for the flight requirements contained in subpart B of part 25.
>
> In these special conditions, the multiplying factors used to determine the minimum operating speeds were reduced in order to maintain equivalency with acceptable operating speeds used by previous transport category airplanes. Since the 1-g stall speed is generally higher than the minimum speed obtained in the stalling maneuver, retaining the current multiplying factors would have resulted in higher minimum operating speeds for airplanes using the 1-g stall speed as a basis for the reference stall speed. However, increasing the minimum operating speeds could impose costs on operators because payloads might have to be reduced to comply with the regulations at the higher operating speeds under some performance-limited conditions. Based on the service experience of the current fleet of transport category airplanes, the costs imposed would not be offset by a commensurate increase in safety.

Finally, Reference 19 notes that the reduced multiplying factors applied to the V_{S1g} stall speed for airplanes with “novel flight control systems” are also appropriate for airplanes with *conventional* flight control systems, since they result in “minimum operating speeds equivalent to the speeds that have been found acceptable in operational service:”

> Several airplane types with conventional flight control systems have also been certificated using the 1-g stall speed as a lower limit to the reference stall speed. Because of the potential deficiencies in using the minimum speed demonstrated in the stalling maneuver, the FAA has been encouraging applicants to use the 1-g stall speed methodology in lieu of the minimum speed obtained in the stalling maneuver. Applicants generally desire to use 1-g stall speeds because the 1-g stall speeds are less dependent on pilot technique and other subjective evaluations. Hence, 1-g stall speeds are easier to predict and provide a higher level of confidence for developing predictions of overall airplane performance. Again, reduced multiplying factors are applied to the 1- g stall speeds to obtain minimum operating speeds equivalent to the speeds that have been found acceptable in operational service. Using 1-g stall speeds ensures that the airplane’s minimum operating speeds will not be unreasonably low.

In sum, for all transport-category airplanes, 14 CFR Amendment 25-108 resulted in:

- Changing the reference stall speed from V_S to V_{S1g}.

- A reduction in the multiplying factors applied to the reference stall speed to obtain minimum operating speeds. In particular, the multiplying factor on to obtain V_{2min} was reduced from 1.2 to 1.13.

The final language of FAR §25.103(a) defining the stall speed reads as follows:

§ 25.103 Stall speed.

(a) The reference stall speed, V_{SR}, is a calibrated airspeed defined by the applicant. V_{SR} may not be less than a 1-g stall speed. V_{SR} is expressed as:

$$V_{SR} \geq \frac{V_{C_{Lmax}}}{\sqrt{n_{ZW}}}$$

where:

$V_{C_{Lmax}}$ = Calibrated airspeed obtained when the load factor-corrected lift coefficient

$$\left(\frac{n_{ZW}W}{qS}\right)$$

is first a maximum during the maneuver prescribed in paragraph (c) of this section. In addition, when the maneuver is limited by a device that abruptly pushes the nose down at a selected angle of attack (e.g., a stick pusher), $V_{C_{Lmax}}$may not be less than the speed existing at the instant the device operates;

n_{ZW} = Load factor normal to the flight path at V_{CLMAX}
W = Airplane gross weight;
S = Aerodynamic reference wing area; and
q = Dynamic pressure.

It should be noted that GAC airplane models prior to the GVI incorporate a stick pusher, and so $V_{C_{Lmax}}$ for these airplanes is defined by the pusher activation speed. Stall protection on the production G650 will consist of a fly-by-wire High Incidence Protection Function (HIPF), whereby the flight control system will prevent the pilot from pulling the airplane into a free-air stall[24]. $V_{C_{Lmax}}$ for this system will be the speed attained with the control column at its aft stop, corresponding to the highest α allowed by the HIPF (the HIPF was under development and therefore unavailable for field performance testing, and so stall protection for these tests consisted of the stick-shaker).

Effect of FAR Amendment 25-108 on the G650 field performance takeoff speeds

Reference 19 states that “since the 1-g stall speed is generally higher than the minimum speed obtained in the stalling maneuver, retaining the current multiplying factors would have resulted in higher minimum operating speeds for airplanes using the 1-g stall speed as a basis for the reference stall speed.” However, because the stall on GAC airplanes is usually indicated by a roll rather than a pitch-down, it is not the case for these airplanes that “the 1-g stall speed is generally higher than the minimum speed obtained in the stalling maneuver,” and so the new multipliers introduced by Amendment 25-108 had the effect of reducing the minimum required operational speeds for the G650, compared to previous GAC models. As explained by the GAC SSAA,

[24] See References 7, 9, and 13 of the *Aircraft Performance Study* (Reference 1).

> … normally when performing aerodynamic stall testing at Gulfstream the aircraft is trimmed at some speed above stall and decelerated from this point at 1kt/sec until the aircraft experiences aerodynamic stall, usually identified on our aircraft by a roll off and NOT by a nose down pitch. The occurrence of wing roll off identifies the point at which the wing is generating maximum usable lift in that condition. At this point the load factor on the aircraft can be slightly less than or greater in some cases than 1g. The speed at which the aerodynamic stall occurs is corrected back to 1-g flight based upon the load factor at the point of departure. This is the approach used on the G650 and earlier models. In effect, we use a VS-1G approach to define our aerodynamic stall speed and not a VSMIN approach. The difference between the VS-1G and VSMIN basis from Gulfstream's standpoint is more so in the factor applied to the reference stall speed, VSR, used to develop take-off safety speeds … [Reference 34, emphasis in original].

For aircraft certified prior to Amendment 25-108, GAC was using a V_{S1g} stall speed to define aerodynamic stall, using a stick pusher to provide margin from this stall, and applying the (larger) multipliers (corresponding to a reference speed based on V_S) to the pusher speed to define minimum operating speeds. Thus, the minimum operational speeds on these GAC aircraft are “conservative” (provide larger margins to stall) relative to the minimum speeds obtained from the smaller multipliers introduced by Amendment 25-108, that Reference 19 states “have been found acceptable.” The minimum operational speeds used for the G650 field performance tests at Roswell used the smaller multipliers together with a V_{SR} defined by a safety margin from V_{S1g}, and so were fully consistent with the updated pairing of the V_{S1g} stall speed and smaller multipliers introduced by Amendment 25-108 and described in Reference 19. Nonetheless, these speeds provided smaller minimum allowable margins to stall relative to previous GAC models, since the stall speed definition was the same (V_{S1g}), but the multipliers on the stall speed were reduced. The stall margin for the G650 relative to previous models was further reduced by a reduction in the margin between V_{SR} and V_{S1g}, as described further below.

Margin between α_{SR} and α_{1g} for the G650 and previous GAC models

As described above, certain minimum operational speeds defined in the FARs are specified as multipliers on a stall reference speed (V_S prior to Amendment 25-108, and V_{SR} following Amendment 25-108). Per Amendment 25-108, V_{SR} itself cannot be less than V_{S1g}. However, if the airplane has a stick pusher, V_{SR} cannot be less than the speed at which the pusher activates. This difference is relevant when comparing the stall margin between previous GAC models and the G650, since the former use stick pushers, but the G650 does not (stall protection is provided by the HIPF system).

The actual speed at which an airplane will stall depends on its weight, and so it is easier to compare stall margins in terms of α, since α_{stall} for a given configuration largely independent of speed or weight.[25] Thus, the following discussion will use the reference stall angle of attack (α_{SR}) instead of V_{SR}, and the 1-g stall angle of attack (α_{1g}) instead of V_{S1g}.

GAC models prior to the G650 incorporate a stick pusher that activates at an α_{pusher} that is typically[26] 2° lower than α_{1g}; as described in Reference 16,

> The Gulfstream IV … like its predecessors, the Gulfstreams II and III, … employs a stall prevention system to preclude attaining the aerodynamic stall in any flight configuration. This is a "stick pusher"

[25] Mach number also affects α_{stall}, but this effect is ignored for the purposes of this discussion.
[26] This margin is at least 2° for the GIV and GV (the models immediately preceding the GVI), but is 1° for the GII and GIII [Reference 8, p. 14].

> system designed to prevent the attainment of very high angle of attack, deep stall, attitudes. The pusher is conservatively set to fire two degrees angle of attack prior to the primary aerodynamic stall. Thus the normal "stall" in Gulfstreams is defined by the pusher actuation, not by the aerodynamic stall [Reference 16, p.1].

Reference 16 also reflects the SSAA's explanation that the aerodynamic stall on GAC aircraft is "usually identified … by a roll off and NOT by a nose down pitch:"

> Prior to the development of this stall improvement Package [for the GIV], the pusher-off aerodynamic stall had been thoroughly explored in the process of defining the pusher angle of attack schedule and learning the aircraft's aerodynamic characteristics. The aerodynamic stall was often characterized by a rolloff to substantial bank angles that could not be arrested without a reduction in angle of attack. The abruptness and the amount of the roll-off was influenced by the setting of the high lift flaps. The most gradual stall was with flaps retracted, the most abrupt was with full flaps [Reference 16, p. 2].

Hence, α_{1g} on GAC aircraft (including the G650) is defined by the angle of attack at which the roll-off occurs. On the two models immediately preceding the G650 (the GIV and GV), α_{pusher} is set ≈ 2° lower than this α_{1g}, and α_{SR} is set equal to α_{pusher}, minus some small margin to account for manufacturing tolerances in the air-data system. Therefore, on these aircraft there is at least a 2° margin between α_{SR} and α_{1g}.

On the G650 at the time of the accident, α_{SR} was set 0.5° below a conservative fairing of α_{1g}, minus 0.34° to account for tolerances in the air-data system (for a total 0.84° difference between α_{SR} and α_{1g})[27]. Therefore, if the tolerances on the air-data systems are roughly the same for the G650 and previous models, then α_{SR} on the G650 was set about 2° - 0.5° = 1.5° closer to α_{1g} than on the previous models. This difference in the definition of α_{SR} adds to the effects of lower multipliers on V_{SR} that make the minimum operational speeds on the G650 closer to V_{S1g} compared to previous models. In other words, both the reduced margin between α_{SR} and α_{1g} and the smaller multipliers on V_{SR} result in minimum operational speeds for the G650 that provide less stall margin than on previous models. This reduced margin allows for more of the available performance to be extracted from the airplane, while the fly-by-wire HIPF system prevents an increase in α above α_{SR}. As noted above, on the accident flight the HIPF was under development and therefore unavailable, and so stall protection for this flight consisted of the stick-shaker.

The reduction in stall margin on the G650 produced by the new V_{SR} multipliers in Amendment 25-108 and the higher α_{SR} afforded by the replacement of the stick pusher with the HIPF can be further quantified by comparing the minimum V_2 speeds required for the G650, and for previous GAC models.

The minimum V_2 speed required on the G650 ($V_{2:650}$) and previous GAC models ($V_{2:prev}$) are specified by their respective certification bases as follows:

$$V_{2:650} = 1.13\ V_{SR:650} \qquad \text{(14 CFR Amendment 25-108)} \qquad [23]$$

$$V_{2:prev} = 1.2\ V_{SR:prev} \qquad \text{(prior to 14 CFR Amendment 25-108)} \qquad [24]$$

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[27] Reference 7, slide 6.

Where $V_{SR:650}$ and $V_{SR:prev}$ are the V_{SR} speeds for the G650 and previous models, respectively. Thus,

$$\frac{V_{2:prev}}{V_{2:650}} = \frac{1.2\,V_{SR:prev}}{1.13\,V_{SR:650}} = 1.062\left(\frac{V_{SR:prev}}{V_{SR:650}}\right) \quad [25]$$

Equation [25] indicates that the minimum V_2 on previous GAC models is about 6% higher than on the G650 due to the changes introduced in Amendment 25-108 alone, assuming that $(V_{SR:prev}/V_{SR:650})$ = 1.0. However, because α_{SR} is closer to α_{1g} on the G650 than on previous models, $(V_{SR:prev}/V_{SR:650})$ > 1.0, and so the V_2 difference is greater than 6%, as shown below.

For 1-g, level flight, the lift L matches the airplane weight W and can be written:

$$L = W = C_L\left(\frac{1}{2}\rho V^2\right)S = \left(\frac{\partial C_L}{\partial \alpha}\right)(\alpha - \alpha_0)\left(\frac{1}{2}\rho V^2\right)S \quad [26]$$

Where ρ is the air density, V is airspeed, and S is the wing area. Solving Equation [26] for V,

$$V = \sqrt{\frac{2W}{\rho S(\partial C_L/\partial \alpha)(\alpha - \alpha_0)}} \quad [27]$$

Noting that $\alpha = \alpha_{SR}$ at V_{SR}, and that

$$\alpha_{SR} = \alpha_{1G} + \Delta\alpha_{margin} \quad [28]$$

Where $\Delta\alpha_{margin}$ is the α margin between α_{SR} and α_{1G}, it follows from Equation [27] that

$$V_{SR} = \sqrt{\frac{2W}{\rho S(\partial C_L/\partial \alpha)(\alpha_{1g} + \Delta\alpha_{margin} - \alpha_0)}} \quad [29]$$

Writing Equation [29] for the previous GAC models and for the G650, and then dividing to get the ratio between $V_{SR:prev}$ and $V_{SR:650}$ gives:

$$\frac{V_{SR:prev}}{V_{SR:650}} = \sqrt{\left(\frac{2W}{\rho S}\right)_{prev}\left(\frac{\rho S}{2W}\right)_{650}\frac{\left[(\partial C_L/\partial \alpha)(\alpha_{1g} + \Delta\alpha_{margin} - \alpha_0)\right]_{650}}{\left[(\partial C_L/\partial \alpha)(\alpha_{1g} + \Delta\alpha_{margin} - \alpha_0)\right]_{prev}}} \quad [30]$$

If the previous models and the G650 have a similar wing loading (W/S) and similar lift-curve slopes $(\partial C_L/\partial \alpha)$, then Equation [30] simplifies to

$$\frac{V_{SR:prev}}{V_{SR:650}} = \sqrt{\frac{\left[(\alpha_{1g} - \alpha_0) + \Delta\alpha_{margin}\right]_{650}}{\left[(\alpha_{1g} - \alpha_0) + \Delta\alpha_{margin}\right]_{prev}}} \quad [31]$$

An estimate of the value of Equation [31] can be obtained by assuming that the value of $(\alpha_{1g} - \alpha_0)$ for the G650 is representative of that for previous models, and using the actual values of $\Delta\alpha_{margin}$ for the G650 and the previous models. With this approach, for the (free air) accident conditions

α_{1g} = 14.7°
α_0 = -1.25°

$\Delta\alpha_{margin:650}$ = -0.5° - 0.34° = -0.84°
$\Delta\alpha_{margin:prev}$ = -2.0° - 0.34° = -2.34°

$$\frac{V_{SR:prev}}{V_{SR:650}} = 1.054 \qquad [32]$$

Thus, the V_{SR} derived using the $\Delta\alpha_{margin}$ used on previous GAC models (i.e., a 2° margin[28] between α_{pusher} and α_{1g}) is about 5% higher than the V_{SR} derived using the $\Delta\alpha_{margin}$ used on the G650 (i.e., a 0.5° margin between α_{SR} and α_{1g}).

Substituting the value of $V_{SR:prev}/V_{SR:650}$ from Equation [32] into Equation [25] gives

$$\frac{V_{2:prev}}{V_{2:650}} = 1.062\left(\frac{V_{SR:prev}}{V_{SR:650}}\right) = (1.062)(1.054) = 1.119 \qquad [33]$$

Consequently, the minimum V_2 determined using the regulations and $\Delta\alpha_{margin}$ applicable to previous GAC models is about 12% higher than that determined using the regulations and $\Delta\alpha_{margin}$ applicable to the G650. As discussed further below, the takeoff speed schedules developed for G650 field performance testing were based on a decision to make the target V_2 speeds for these tests equal to the minimum V_2 permitted by Amendment 25-108. As a result, during the G650 field performance tests, the airplane was being operated at lower speeds, and with a smaller margin to stall, than it would have been had the G650 minimum V_2 speeds been derived using the same certification basis and $\Delta\alpha_{margin}$ as previous GAC airplanes.

The reduction in stall margin resulting from the reduced multiplying factors described above is recognized by the FAA in Advisory Circular (AC) 25-7B, *Flight Test Guide for the Certification of Transport Category Airplanes* (Reference 35):[29]

> Although the reduced multiplying factors were intended to result in roughly equivalent operating speeds, there is one class of airplanes for which a significantly lower operating speed would be obtained. Airplanes equipped with a device that abruptly pushes the nose down (e.g., a stick pusher) near the angle-of-attack for maximum lift would be operated at speeds and angles-of-attack closer to the pusher activation point than has been experienced in operational service. Therefore, to maintain equivalency in operating speeds for these airplanes, a supplementary margin has been established such that V_{SR} must not be less than the greater of 2 knots or 2 percent above the speed at which the device activates (§ 25.103(d)) [Reference 35, pp. 118-119].

[28] The 2° margin for the GIV and GV is used here; the margin for the GII and GIII is 1°.
[29] AC 25-7A, not AC 25-7B, is relevant to the G650 certification. Language pertaining to the reduced multiplying factors introduced with the definition of V_{SR} in Amendment 25-108 of the FARs do not appear in AC 25-7A. However, all other references to AC 25-7B in this *Addendum* point to language that is identical in AC 25-7A.

Role of V_{mu} and V_{LO} in the takeoff speed regulations

Before the development of the takeoff speed schedules is discussed further, it is helpful to describe two additional speeds used to regulate allowable values of V_R. These are the minimum unstick speed (V_{mu}) and the lift-off speed (V_{LOF} or V_{LO}), defined in FAR 25.107(d) and 25.107(f), respectively:

> §25.107(d) V_{mu} is the calibrated airspeed at and above which the airplane can safely lift off the ground, and continue the takeoff. V_{mu} speeds must be selected by the applicant throughout the range of thrust-to-weight ratios to be certificated. These speeds may be established from free air data if these data are verified by ground takeoff tests.
>
> …
>
> §25.107(f) V_{LOF} is the calibrated airspeed at which the airplane first becomes airborne.

Hence, V_{mu} is the *slowest* demonstrated V_{LO} at a given thrust-to-weight ratio (T/W), as determined by flight testing.

V_{mu} and V_{LO} regulate the allowable values of V_R through FAR 25.107(e)(1)(iv):

> §25.107(e)(1) V_R may not be less than – … (iv) A speed that, if the airplane is rotated at its maximum practicable rate, will result in a V_{LOF} of not less than 110 percent of V_{mu} in the all-engines-operating condition and not less than 105 percent of V_{mu} determined at the thrust-to-weight ratio corresponding to the one-engine-inoperative condition.

In addition, FAR 25.107(e)(1)(ii) specifies that V_R may not be less than 105% of the minimum control speed (V_{MC}) with the critical engine inoperative (as defined in FAR §25.149(b)).

FAR 25.107(e)(1)(iii) specifies that V_R may not be less than "the speed (determined in accordance with §25.111(c)(2)) that allows reaching V_2 before reaching a height of 35 feet above the takeoff surface." In other words, if the airplane reaches a height of 35 ft. AGL before accelerating to V_2, then V_R is too low. Accelerating to V_2 before reaching 35 ft. AGL is required by §25.111(c)(2).

Consequently, the values of V_{mu} demonstrated during flight test are one basis for the lower boundary of allowable takeoff rotation speeds, just as V_{SR} (and ultimately V_{S1g}) are one basis for the lower boundary of allowable V_2 speeds for the initial climb following takeoff. V_2 itself (and therefore V_{S1g}) also place a lower bound on V_R through §25.107(e)(1)(iii). Reference 21 states that for the G650, V_R is limited by the V_{MC} requirement (§25.107(e)(1)(ii)) for weights below 70000 lb., and by the V_2 requirement at 35 ft. (§25.107(e)(1)(iii)) for weights above 70000 lb. However, as noted below, prior to the start of the Roswell II field performance testing, the GAC Principal Engineer for Airplane Performance (PE) noted that the speed schedules developed for this testing were "marginal" and on the "ragged edge" of meeting the V_{mu} requirements of §25.107(e)(1)(iv).

For the G650, the runway length required to take off is minimized if V_2 is minimized, and so there is a performance advantage to keeping this speed as close to the minimum required as possible.

Takeoff rotation abuse requirements

In addition to the requirements described above regarding takeoff speed relationships during normal takeoffs, FAR §25.107 also contains regulations that consider "abused" takeoffs, in order to provide additional safety margin to account for "reasonably expected service variations." In particular, FAR 25.107(e)(4) states that

> Reasonably expected variations in service from the established takeoff procedures for the operation of the airplane (such as over-rotation of the airplane and out-of-trim conditions) may not result in unsafe flight characteristics or in marked increases in the scheduled takeoff distances established in accordance with §25.113(a).

Per the guidance in AC 25-7B, the requirement of §25.107(e)(4)

> … has been interpreted as requiring takeoff tests with all engines operating with:
> (aa) An abuse on rotation speed, and
> (bb) Out-of-trim conditions, but with rotation at the scheduled V_R speed.
>
> **NOTE:** The expression "marked increase" in the takeoff distance is defined as any amount in excess of one percent of the scheduled takeoff distance. … [Reference 35, p. 27].

Regarding the early-rotation abuse test, AC 25-7B states that

> For this demonstration, the airplane should be rotated at a speed 7 percent or 10 knots, whichever is less, below the scheduled V_R. Tests should be conducted at a rapid rotation rate or should include an overrotation of 2 degrees above normal attitude after liftoff [Reference 35, p. 27].

FAR 25.107(e)(3) contains a requirement pertaining to one-engine inoperative takeoffs:

> It must be shown that the one-engine-inoperative takeoff distance, using a rotation speed of 5 knots less than V_R … does not exceed the corresponding one-engine-inoperative takeoff distance using the established V_R.

AC 25-7B notes that "the airspeed attained at the 35 ft. height during this test should not be less than the scheduled V_2 value minus 5 knots."

In addition, AC 25-7B states that regarding stall warning during the takeoff speed abuse tests,

> The presumption is that if an operational pilot was to make an error in takeoff speeds that resulted in an encounter with stall warning, the likely response would be to recover aggressively to a safe flight condition rather than making a conscious effort to duplicate the AFM takeoff performance data. Therefore, the activation of any stall warning devices, or the occurrence of airframe buffeting during takeoff speed abuse testing, is unacceptable [Reference 35, p. 28].

This guidance in AC 25-7B indicates that the final V_R scheduled for the airplane must not only satisfy the minimum bounds specified by the V_{mu} tests through §25.107(e)(1)(iv) and by V_2 through §25.107(e)(1)(iv), but must also provide for an over-rotation margin of 2° without activating the stall warning (or the HIPF, in the case of the G650). The rotation abuse requirements of §25.107(e)(4) will tend to drive V_R upwards, so as to lower the pitch attitude for normal takeoffs and increase the margin from stall (and stall warning / HIPF activation).

III. Takeoff speeds development for G650 Roswell I & II field performance testing

Minimum Unstick Speed (V_{mu}) tests as a precursor to takeoff speed development

GAC document GVI-FT-003, *Model GVI Data Analysis Methods*, dated June 25, 2009 (Reference 20) "presents data analysis methods and flight test procedures (where applicable) which are to be used during the GVI Development, Company (pre-Type Inspection Authorization) and Certification flight test phases" (p. 2). Section 9 of Reference 20 describes the methods to be used to develop the takeoff speed schedules for the G650 field performance tests, and, ultimately, the final AFM. Section 8 of Reference 20 describes V_{mu} testing and the role of this testing in the planned development of the takeoff speed schedules.

Section 8.1 of Reference 20 provides relevant information regarding the philosophy underlying the takeoff speed schedule development methods described in Section 9 of the document:

> As defined in FAR 25.107(d), the Minimum Unstick Speed, V_{MU}, "is the calibrated airspeed at and above which the airplane can safely lift off the ground, and continue the takeoff." It is alternatively referred to in AC 25-7A as the speed at which airplane weight is just supported by lift and thrust forces, for a given critical attitude (C_{LMAX}, tail bump, or stall angle-of-attack). V_{MU} is not an operational speed, but rather, is used as a constraint in the definition of operational rotation and liftoff speeds.
>
> The GVI may not [sic] be geometry limited due to a larger horizontal tail increasing tail power, and a shorter landing gear strut. Additionally, there is uncertainty regarding air flow characteristics of the wing in the presence of ground effect which, on the G-IV, led to unanticipated premature wing stall. Since V_{MU} is selectable by the applicant, it has been GAC's tradition not to attempt demonstration of absolute minimum V_{MU} speed as per the definition because of the reasons cited. Instead, demonstrated speeds are selected sufficiently low enough to comply with FAR 25.107, but still well above aerodynamic stall.
>
> Demonstrated V_{MU} speeds are normally used as the basis from which the normal speed schedules are developed (V_1, V_R, V_2). An extensive matrix of test conditions covering the entire range of T / W ratios of each certified takeoff configuration is tested. Then rotation and liftoff speed increments are added to the V_{MU} baseline speeds to work forward to the operational speeds (See Section 9.0). However, it was determined during G-IV certification testing that rotation and liftoff from V_{MU} based speed schedules resulted in V_2 speeds slightly less than the required $1.2V_S$. This in turn, led to a redefinition of the speed schedules based upon the V_2 requirement at 35 ft. Appropriate increments were then subtracted from the V_2 requirement to work backwards to V_{LO} and V_R. The resulting liftoff speeds were then checked against FAR 25.107 (e)(1)(iv) requirements to be above 105 and 110 % of V_{MU} for single and all-engine cases, respectively.
>
> Therefore, only a minimal number of V_{MU} tests will be used to demonstrate compliance with FAR 25.107. As per AC 25-7A Change 1 guidelines, critical single engine and all-engine T / W ratios will be tested at speeds of 5 and 10% (plus some margin) below anticipated normal liftoff speeds. These demonstrated worst case speeds will then be used as reference for all T / W conditions during liftoff speed schedule determination.
>
> V_{MU} will be tested for both 10° and 20° flaps at the critical T / W ratios for both engines operating and one engine inoperative. However, rather than conducting actual single engine takeoff tests, AC 25-7A Change 1 allows all-engine operation at thrust levels consistent with single engine operation. The results of the simulated engine inoperative tests will be analytically adjusted to account for asymmetric trim drag that would have been required to counter asymmetric thrust (See Section 12).
>
> …
>
> > *Note: Initial target rotation speeds and pitch attitudes will be based upon estimated stalling speed in ground effect from wind tunnel results, and limited by estimates of pitch authority, lateral-directional controllability, and minimum climb gradients. Initial V_{MU} tests will require a

"build-down" approach to these estimated speeds in order to safely explore the behavior of the wing in ground effect.

Some observations regarding this excerpt are as follows:

- The authors of the document were aware of the roll-off and wingtip strike on the GIV test program that resulted from a stall in ground-effect, and noted that this event indicates that “there is uncertainty regarding the flow characteristics of the wing in the presence of ground effect.”

- This uncertainty is part of the reason that “it has been GAC’s tradition not to attempt demonstration of absolute minimum V_{mu} speed ….”

- Further, “initial V_{mu} tests will require a ‘build-down’ approach to these estimated speeds in order to safety explore the behavior of the wing in ground effect.”

- These statements in Reference 20 suggest that the authors were aware of the “uncertainty” in the “estimated stalling speed in ground-effect from wind tunnel results,” and of the potential for $\Delta\alpha_{stall,IGE}$ to be larger than estimated. This awareness is remarkable given the lack of analysis and limited understanding of the roll-off events on flights 88 and 132, described above.

- Reference 20 cites the minimum V_2 required as 1.2 V_S, which corresponds to the requirement prior to FAR Amendment 25-108. The actual requirement for the GVI, which is to be certified to Amendment 25-108, is that V_2 be no less than 1.13 V_{SR}, as described above. In the end, as discussed below, the actual V_2 speeds scheduled for the G650 field performance testing were based on 1.13 V_{SR}.[30]

- The “normal” method for developing V_1, V_R, and V_2 is to use V_{mu} as the “basis” and then “work forward” to the operational speeds.

- On the GIV program, this “normal” method led to V_2 speeds that were *below* the requirement that $V_{2min} \geq 1.2\ V_S$.

- Consequently, on the GIV program, V_2 was established as the minimum required by regulation (1.2 V_S), and “appropriate increments were then subtracted from the V_2 requirement to work backwards to V_{LO} and V_R.”

- This same approach was adopted for the G650, but with V_2 established as 1.13 V_{SR}. However, unlike on the GIV program, it was not established beforehand that “working forward” from V_{mu} to V_2 on the G650 would result in V_2 speeds lower than V_{2min}, which was the rationale for “working backwards” from V_2 to V_R on the GIV.

[30] The PE confirmed that “for the *GVI Data Reduction Plan*, the V_2 speed criteria should have been changed to reflect $V_2 \geq 1.13\ V_{SR}$, where V_{SR} is based on the new 1G stall speed criteria” [Reference 27].

- As a result, during the field performance tests the G650 was being operated at lower airspeeds, higher angles of attack, and smaller margins to stall than previous GAC programs (as discussed above).[31]

- The statement that the "demonstrated worst case [V_{mu}] speeds will … be used as reference for all T / W conditions during liftoff speed schedule determination" implies that the results of the V_{mu} tests are intended to be analyzed and used in the development of the takeoff speed schedules for field performance testing. The use of the V_{mu} data for takeoff speed development is also indicated by statements in Section 9 of Reference 20 (see below). However, as will be seen, the results of the V_{mu} tests were not used in the development of the takeoff speed schedules for the field performance tests during Roswell II, and in fact the GAC G650 Performance Group in Flight Sciences (who developed the takeoff speeds) did not receive a copy of Reference 6 (the draft V_{mu} report prepared by FTE-1) until after the accident.

Takeoff speed schedule development process per GVI-FT-003

Section 9 ("Takeoff Performance") of Reference 20 states the following in sub-section 9.1, "Test Procedure:"

> This portion of the data reduction plan concerns the determination of takeoff distance and takeoff speed schedules as required by FAR 25.105 through FAR 25.113. In advance of testing, a preliminary flight manual will be prepared and updated to reflect the results of airspeed calibration, minimum control speed, minimum unstick speed, and stall speed tests. This update is for the purpose of refining original analytical estimates of takeoff speed schedules, thus providing a more accurate data base for establishing target test speeds.
>
> Three types of tests are involved:
>
> • All Engines Operating Takeoff
> • One Engine Failed Takeoff
> • Aborted Takeoff - Single Engine

Consistent with the information presented in the section describing V_{mu} tests, this information indicates that V_{mu} data is among that to be used "in advance of testing … for the purpose of refining original analytical estimates of takeoff speed schedules."

The method for the development of the takeoff speed schedules is described in sub-section 9.2.3 of Reference 20, titled "Takeoff Speed Schedules," which states:

> Takeoff speed schedules consist of Takeoff Rotation Speed, V_R, Liftoff Speed, V_{LO}, Takeoff Safety Speed, V_2, and Screen Height Speed, V_{35}. The schedules are normally presented in terms of a ratio to stall speed, V / V_S, and are developed from the observations of speed increments experienced during normal one and two engine takeoff test runs. Takeoff speeds are developed in accordance with FAR 25.107, which specify a number of requirements that the selected operational speeds must satisfy. As discussed in Section 8.0, the GVI takeoff speeds will be developed under the same theory of takeoff distance optimization as was developed during G-IV certification testing. Therefore, rather than using V_{MU} as the basis, the new starting point for speed schedule development will be the establishment of V_2 at 35 ft. above the runway (single engine operation). V_2 is specified in FAR 25.107 as the higher of 120% of V_S, or 110% of V_{MCA} as defined in Section 2.6. G-IV experience has shown that V_{MCA} is sufficiently low

[31] As discussed in Section D-IV, since the accident GAC has changed the methods it uses for takeoff airspeed development and testing. The new methods are founded on simulation and modeling, and have resulted in higher takeoff speeds for the G650 than what were in use during the Roswell II tests.

> as to not affect V_2 determination for any conditions, and it is anticipated that the same situation will exist for the GVI.
>
> The initial target V_R and V_{LO} schedule used for the takeoff testing will be based upon analytical estimates, and updated based on the results of performance stall tests of Section 5.0, and V_{MCA} and V_{MU} tests if necessary. Testing will be conducted according to procedures developed for GVI operational use, and will be similar to the following procedures used for the G-IV certification testing:
>
> All Engines Operating:
>
> • Set EPR on both engines to maximum allowed values with brakes on.
> • Release brakes and advance throttles, if necessary, to the target takeoff EPR setting before the speed of *TBD* knots is reached.
> • Accelerate to the target rotation speed (V_R), using normal rotation techniques, rotate and climbout at target attitude until 35 ft above ground level (AGL).
> • Initiate gear retraction after 35 AGL.
> • Maintain the airspeed (V_{35}) attained at 35 feet and climbout to 200 ft AGL.
>
> One Engine Inoperative:
> • Set EPR on both engines to maximum allowed values with brakes on.
> • Release brakes and advance throttles, if necessary, to the target takeoff EPR setting before the speed of *TBD* knots is reached.
> • Accelerate to the engine failure speed (V_{EF}), then simulate an engine failure by:
>
> 1. Idle Cut -- Abruptly retarding a throttle for one engine to Idle, or...
> 2. Fuel Cut -- Shutting fuel off to one engine
>
> • Continue the takeoff to target rotation speed (V_R), using normal rotation techniques, rotate and climbout at target attitude to35 ft above ground level (AGL).
> • Initiate gear retraction after 35 AGL.
> • Maintain the airspeed (V_2) attained at 35 feet and climbout to 200 ft AGL.

This section in Reference 20 then goes on to outline the details of how the available takeoff data from flight tests are to be used to generate actual speed decrements from V_{35} to V_{LO} and from V_{LO} to V_R, as a function of T/W. V_{LO} is then updated by applying the V_{35} to V_{LO} decrement to the target V_2 (1.2 V_S per GVI-FT-003, but actually 1.13 V_{SR} for the G650). V_R is similarly updated by applying the V_{LO} to V_R decrement to the (updated) V_{LO}. At this point,

> The resulting V_R / V_S schedule must then be checked against several criterion specified in FAR 25.107(e). The first criteria of paragraph (ii) states that rotation speeds must be higher than 105% of V_{MCA}. The second criteria of paragraph (iv), states that if the airplane is rotated at its *maximum practical rate*, the airplane should not liftoff at a speed lower than 110% of V_{MU} for all-engines operating, and 105% of V_{MU} for single engine operating. …
>
> … The two engine test runs will be processed in a similar manner. However, an additional requirement on takeoff speeds is imposed by FAR 25.107 (e)(2) which stipulates that a single value of rotation speed must be selected to show compliance with both single and all-engine operating takeoff provisions. Compliance is accomplished by selecting the higher of the V_R / V_S schedules determined using the above described procedures for single and all-engine takeoff tests. It is anticipated that the single engine V_R / V_S schedules will be the higher of the two, as was experienced during G-IV certification tests. Therefore, the all-engines operating V_R / V_S schedules will be adjusted upward to match the single engine schedules, and then the V_{LOF} / V_S and V_{35} / V_S will also be adjusted on a point-for-point basis. Finally, the adjusted all-engines operating V-speed schedules will be checked against the criterion of FAR 25.107 (e) (ii)&(iv), which stipulate that V_R / V_S must be higher than 105% of VMCA and 110% of V_{MU}, respectively [Reference 20, pp. 61-62].

Some observations regarding this excerpt are as follows:

- The method described in this section uses V_2 rather than V_{mu} as the "new starting point for speed schedule development," in keeping with "the same theory of takeoff distance optimization as was developed during G-IV certification testing."

- The initial V_R and V_{LO} schedules are intended to be "updated based on the results of performance stall tests …, and V_{MCA} and V_{MU} tests if necessary." This is consistent with the earlier statement indicating that V_{mu} data is among that to be used "in advance of testing … for the purpose of refining original analytical estimates of takeoff speed schedules."

- The procedures for both the one-engine-inoperative (OEI) and all-engines-operating (AEO) takeoffs instruct the pilot: "accelerate [or continue the takeoff] to the target rotation speed (V_R), using normal rotation techniques, rotate and climbout at target attitude until 35 ft. above ground level (AGL)." Hence, per these procedures the target pitch attitude is not to be exceeded until the airplane reaches 35 ft. AGL (and V_2, presumably). This procedure is different than that specified in the OEI test card for the accident run, which instructs the pilot: "maintain target pitch attitude until V_2 is achieved, then transition to speed." Hence, if V_2 is achieved below 35 ft. AGL (or even on the ground), the test card procedure does not preclude the pilot from increasing pitch above the rotation target in order to maintain V_2.

- The V_{mu} test results are to be used to confirm that the final V_{LO} meet the criteria of FAR §25.107(e)(iv) ($V_{LO} \geq 1.05\ V_{mu}$ for OEI and $V_{LO} \geq 1.10\ V_{mu}$ for AEO).

- There is no reference to using speed ratios from prior airplane programs to generate the takeoff speed schedules for the G650. Instead, the required ratios are "developed from the observations of speed increments experienced during normal one and two engine takeoff test runs" *with the G650*, not another airplane.

The takeoff speed schedules for the Roswell II G650 field performance tests (starting March 6, 2011) were not developed from takeoff speed increment data gathered during the test program, but rather by applying the V/V_{SR} ratios from a previous GAC model, the G550, to the G650. Furthermore, since the G650 Performance Group did not receive the results of the V_{mu} tests performed at KROW in November 2010 (Roswell I) until May 3, 2011 (about a month after the accident), the V_{LO} schedule developed for Roswell II was not checked comprehensively against the requirements of 25.107(e)(iv) prior to the start of testing. These procedures differ from those outlined in Reference 20. Even so, the PE met with FTE-1 on March 27, 2010 (a few days before the accident) and discussed some of the results of the V_{mu} tests from Roswell I:

> … I think it was Monday the 27th of March, [FTE-1] and I met. I showed him some of the reduced V/V stalls. … I was concerned about whether our liftoff speeds met the necessary V_{MU} margins: 5 percent above the single engine V_{MU}; 10 percent above the twin engine V_{MU}. So we took a look at that and [they were], quite frankly, marginal. We were just on the ragged edge of meeting those V_{MU} limits [Reference 23, p. 17].

Development of G650 takeoff speeds based on G550 V/V_{SR} ratios

As noted above, the takeoff speed schedules for the Roswell II G650 field performance tests were developed by applying the V/V_{SR} ratios from the G550 to the G650. GAC presented this method to NTSB via a *PowerPoint* presentation on June 7, 2011 (Reference 21). Additional information was provided in a *PowerPoint* file emailed to NTSB on January 18, 2012 (Reference 22), in email correspondence between GAC and NTSB, and during interviews with staff in the GAC G650 Performance Group.

Figure 7, which is based on information provided in Reference 22, depicts the V_R/V_{SR}, V_{LO}/V_{SR}, and V_2/V_{SR} ratios for the G550 and G650. As noted, the V_{SR} for the G550 is based on α_{pusher} which has at least a 2° margin to (free-air) α_{stall} (α_{1g}), and the V_{SR} for the G650 is based on α_{SR}, which has a 0.5° margin to α_{stall} (α_{1g}).[32]

The lines for the G650 in Figure 7 are constructed as follows:

$(V_2/V_{SR})_{650}$ is set identically equal to 1.13, the minimum allowed by FAR Amendment 25-108.

$(V_{LO}/V_{SR})_{650}$ and $(V_R/V_{SR})_{650}$ are computed by applying the G550 speed ratio decrements from V_2/V_{SR} to the G650:

$$\left(\frac{V_{LO}}{V_{SR}}\right)_{650} = \left(\frac{V_2}{V_{SR}}\right)_{650} + \left[\left(\frac{V_{LO}}{V_{SR}}\right)_{550} - \left(\frac{V_2}{V_{SR}}\right)_{550}\right] = 1.13 + \left[\left(\frac{V_{LO}}{V_{SR}}\right)_{550} - \left(\frac{V_2}{V_{SR}}\right)_{550}\right] \quad [34]$$

$$\left(\frac{V_R}{V_{SR}}\right)_{650} = \left(\frac{V_2}{V_{SR}}\right)_{650} + \left[\left(\frac{V_R}{V_{SR}}\right)_{550} - \left(\frac{V_2}{V_{SR}}\right)_{550}\right] = 1.13 + \left[\left(\frac{V_R}{V_{SR}}\right)_{550} - \left(\frac{V_2}{V_{SR}}\right)_{550}\right] \quad [35]$$

Interestingly, the $(V_2/V_{SR})_{550}$ plotted in Figure 7 exceeds the minimum of 1.2 required by the FARs (prior to Amendment 25-108) across the T/W_{LO} range (W_{LO} is the airplane weight at lift-off). The PE explained that

> The V_2 on the GV was originally 1.2 V_{Smin}, actually on the GV we were tail power limited such that we actually did not even meet that criteria. We found that if we attempted to rotate at less than about 1.17 V_{Smin} … that the airplane was not very responsive. So most of the takeoff performance particularly at the heavy weight on the GV was limited by tail power we would rotate at 1.17 and typically at a heavy gross weight not get to the 35-foot point until about 1.21, 1.22 V_{Smin}. So even with the GV we were paying a slight performance penalty because if we could have rotated aggressively at a lower speed that would have been beneficial.
>
> With the 650, we have a fully trimmable horizontal and that provided more than enough tail power to rotate the airplane aggressively at lower speeds [Reference 24, pp. 7-8].

It should be noted that the $(V_{LO}/V_{SR})_{650}$ speed ratio plotted in Figure 7 corresponds to a prescribed value of α (and pitch angle θ) at lift-off; different values of θ during rotation and lift-off would result in different values of V_{LO}/V_{SR} (and of V_R/V_{SR}, if the speed increment between V_{LO} and V_R is preserved). According to the PE, the value of θ for the $(V_{LO}/V_{SR})_{650}$ plotted in Figure 7 is between 9° and 10° [Reference 23, p. 7].

Reference 21 indicates that at θ = 10°, the OEI V_{LO} for the accident case is 132 KCAS, 1 knot higher than the V_{LO} that was computed (after the accident) using the in-ground-effect C_L

[32] The G650 incorporates an additional 0.34° margin to account for tolerances in the air-data system.

determined from the V_{mu} data, as presented in Reference 6 (and shown here in Figure 2). At θ = 9°, Reference 21 indicates that the OEI V_{LO} computed using the data in Figure 2 would increase to 136 KCAS, which is 1 knot above the target V_2 speed used on the accident flight. Hence, the G650 speed ratios plotted in Figure 7 most likely correspond to a target θ of 10°, as specified on the original test cards for the flaps 10 OEI maneuver.[33]

The θ targets for the Roswell I field performance testing were established by examining takeoff data from earlier flights. As explained by GAC,

> Prior to Roswell I field performance testing in Nov 2010, countless twin engine takeoffs were conducted using very conservative takeoff speeds that were developed prior to the G650 First Flight in Nov 2009. These first flight takeoff speed criteria formed the basis for establishing the initial start speeds and pitch attitudes for Roswell I field performance testing. Roswell I field performance testing consisted of V_{MU} testing and parametric CTO testing. During the parametric CTO testing, a range of rotation speeds, rotation rates and climbout pitch attitudes were flown. This testing provided guidance on the impact of these parameters on aircraft performance/takeoff distance [Reference 25].

For the Roswell I field performance testing, V_R/V_{SR}, V_{LO}/V_{SR} and V_2/V_{SR} ratios were computed as described above and the resulting V_R, V_{LO} and V_2 speeds were provided to the test crews. However, the V_{LO} and V_2 speeds were not targeted (controlled to) during the Roswell I tests; rather, only the V_R speeds were targeted, and the V_{LO} and V_2 (speed at 35 ft. AGL) achieved were simply recorded:

> Roswell I testing involved parametric variations of rotation speed, rotation rate and climbout pitch attitudes. As such, only rotation speeds were targeted for each of these maneuvers. These target rotation speeds were delivered via email and directly at Roswell …. The resulting V_{LO} and V_2/V_{35} speeds for each of these maneuvers were noted after the test [Reference 25].

Takeoff technique adjustments to achieve target V_2/V_{SR} of 1.13

Following the Roswell I tests, GAC noted that the recorded speeds achieved at 35 ft. AGL were substantially higher than the target V_2 of 1.13 V_{SR} planned for Roswell II. In addition, the takeoff field lengths were longer than what was hoped for; GAC had guaranteed a takeoff field length of 6000 ft., ± 8%, for flaps 20 (no guarantee was made for flaps 10) (Reference 31, p. 14). As a result, the test team experimented with alternative takeoff rotation techniques and rotation speeds so as to try to reduce the V_2 overshoot and takeoff field lengths, and bring them closer to the planned-for values. Changes stemming from this work involved:

- Adding 2 knots to the V_R speed scheduled for a given T/W, while keeping V_{LO} and V_2 the same.

- Increasing θ beyond the target θ specified in the test card as soon as the airplane lifted off (as opposed to holding this target θ until 35 ft. AGL, as was done during Roswell I testing).

- Using a more aggressive column input to initiate rotation, so as to minimize the time to rotate to the target θ. The abruptness and magnitude of this pull evolved over time (see discussion below).

[33] The target pitch angle was later reduced to 9°, as described further below.

Regarding the increase of V_R speeds by 2 knots (while keeping V_{LO} and V_2 the same), the PE explained that

> A decision was reached in early Feb 2011 to conduct a one-day flight test evaluation at Birmingham Intl airport (BHM) to check out some revised takeoff procedures. This testing was conducted on 13 Feb 2011 and consisted of a total of 7 flaps 20[34], simulated[35] OEI CTO runs …. According to notes from [FTE-1] (the Flight Test engineer conducting the Birmingham testing) immediately following this test, "The first 5 runs were at V_R+4, with increasing stick force. The last 2 runs were at V_R+2, with 65-75 initial stick force." The V_R reference for these runs was based on using GV/G550 flaps 20, OEI V/V_Ss shifted to a V_2/V_{SR} of 1.13 for the GVI aircraft. …. As a result of this testing, a decision was made to use calculated GVI V_R speeds shifted up by 2 KCAS as the basis for our target V_R speeds for Roswell II testing. This criteria of V_R+2 resulted in producing slightly lower V_2/V_{SR} speeds while still providing acceptable rotation segment handling characteristics [Reference 28].

The flaps 10 V_R, V_{LO}, and V_2 speed schedules for Roswell I and II are compared in Figure 8. After the accident, GAC estimated that the weight of the airplane was 88000 lb. (Reference 1), though the cockpit video records the crew using speeds corresponding to a weight of 87000 lb. (V_R = 127 knots, V_{LO} = 132 knots, V_2 = 135 knots).

The takeoff procedures evaluated during the Birmingham tests (flight 111 on N652GD) also involved experiments with different rotation strategies and different initial column pull forces to initiate rotation. Regarding the target pitch attitudes for takeoff, the PE explained that

> My understanding was that we needed to adhere to a pitch attitude at liftoff to make sure we met our V_{MU} limits but then after liftoff, we needed -- and the instructions to the pilot community was to start increasing the angle of attack so as to achieve V_2 by 35 feet.
>
> … You pitch-up to a certain attitude for liftoff but after liftoff, then you increase that attitude as you climb out. If we held a constant pitch attitude as we found out during Roswell I in November testing, we were overshooting our speeds by a considerable margin. So it was in February, we went to Birmingham, did some additional testing and during that, after they lifted off, they then started targeting higher pitch attitudes, which in turn cut down the acceleration during the climbout to 35 feet so as to get closer to our V_2 targets. So we were not holding a constant pitch attitude during the latter stages of our testing in order to get closer to our target V_2 speeds.
>
> … even though the cards say maintain pitch attitude to V_2, we were increasing the pitch attitude as we climbed out to minimize the overshoot in speed …. If you maintain your pitch attitude, we were getting entirely too much acceleration and our speeds were going up and our distances were going up. So we did instruct the pilots to once they lifted off to then start pulling back to chase the V_2 before they got to 35 feet rather than hold that pitch attitude until they got to 35 feet because otherwise they were overshooting the target speed by quite a bit higher increments than we were looking for [Reference 23, pp. 9-12].

Coupled to the change in strategy involving the target θ were changes regarding the magnitude and abruptness of the column pull used to initiate rotation. Through an iterative investigation with different pull forces and input rates on flight 111, an abrupt pull force of about 70-75 lb. was found to result in the least amount of speed overshoot. However, prior to the accident flight, this technique was relaxed somewhat; according to a statement of another FTE, during one of the pre-flight briefings the day before the accident, "discussion on appropriate column force was also discussed. [P-2] stated that the previous 70-75 lbs. of pull

[34] The tests conducted at Birmingham all used flaps 20 and a 9° θ target (no flaps 10 takeoffs were performed).
[35] For increased safety, the OEI condition was simulated by using symmetric, reduced thrust on both engines that resulted in a total thrust equivalent to the OEI condition.

force was excessive and 60-65 lbs of pull force was agreed upon" [Reference 26]. In addition, TM-1 stated that during the pre-flight brief

> … the discussion moved to pull force and how to apply pressure to the column. We discussed a slightly slower pull (rather than the ramp input that had been employed previously) to a force of about 60-65 pounds. A comment from [P-1] about the 60 pound target pull force was that it would be more repeatable, and would not be dependent upon jerking the airplane controls around. An objective of slowing the pull technique was to reduce the amount of "bobble" on pitch. This means that the pitch was peaking out, decreasing quite a bit, and then recovering throughout the climb. By slowing the pull technique we hoped to reduce the push that followed liftoff, which consequently reduced the nose attitude, adding time to the liftoff to V_2 portion of the takeoff. [FTE-1] proposed targeting a 6 degree per second [peak] pitch rate, and all agreed that sounded reasonable [Reference 14, p. 3].

Per this statement, the initial column force was reduced from 70-75 lb. to 60-65 lb. in order to reducing the pitch "bobble" during rotation, and "not be dependent upon jerking the airplane controls around."[36]

It is possible that the roll-off event on flight 132 may also have influenced the decision to lower the column pull force for flight 153. Flight 132 was the first takeoff performance flight conducted after flight 111 (the takeoff technique development flight in Birmingham). On flight 111, the G650 project pilot (P-3) was the PIC and PF, and P-2 was the SIC and PM. As mentioned earlier, on flight 132 P-2 was the SIC, but was also in the left seat and the PF, while P-4 was the PIC, and monitoring from the right seat.[37] Unlike flight 111, which "simulated" an OEI condition with symmetric, reduced thrust on both engines, test card 3 for flight 132 was a true OEI takeoff, involving a throttle chop at V_{EF}. Consequently, this takeoff was probably more difficult to perform than those on flight 111, since with a true OEI condition the pilot has to compensate for the asymmetric thrust as well as perform the rotation maneuver.

Test card 3 for flight 132 states, "rotate at Vr using 70 lb pull until rotation begins, reduce force to gradually capture 9° pitch attitude" (Reference 29, p. 58). The on-board video recordings (summarized in Attachment II of Reference 29) indicate that on flight 132, while parked or taxiing on the ground, P-2 "practiced" the column pull to be used for takeoff rotation 18 times prior to the first takeoff, and another couple of times prior to the second takeoff. For some of these practice pulls, FTE-1 indicated the maximum column force applied, and P-4 provided some coaching, including demonstrating how the column should be pulled. FTE-1 indicated that 65 lb. of force would be "good," and "P-4 demonstrated another pull and held it, then said 'it's pretty much of a step input there, if you just pull it like that'" (Reference 29, p. II-35).

As shown in the plots in Appendix A, during the takeoff corresponding to the roll-off event, P-2 pulled with a step input to about 67 lb. (consistent with the guidance from FTE-1 and P-4), but held sufficient column to allow θ to increase past the target of 9°, to about 12°. As θ reached this peak, P-4 pushed abruptly on the column with about 35 lb. of force to lower the nose.

As the airplane was circling to land following this takeoff, and during the final approach, P-4, P-2, and FTE-1 discussed the roll-off event and the fact that P-2 had rotated the airplane

[36] According to TM-1, work by FTE-1 and P-2 in a G650 flight simulator prior to flight 153 may also have influenced this reduction in column forces (see discussion below).

[37] Later in flight 132, P-4 and P-2 traded seats a couple of times, but for the relevant takeoffs discussed here, P-2 was always in the left seat, and P-4 was always in the right [see Reference 29].

before the V_R call (at V_1). FTE-1 pointed out that the stabilizer trim was set 0.6° more nose-up than intended.

Per Reference 29,

> After landing, P-4 said that 0.5 degree of trim does not have much of an effect, and advised "you just gotta intercept it [the target θ], whatever it is." He further advised P-2 to "catch it quicker" and stated that "you're doing a rapid step input, but you gotta, you've got to, intercept the 9 degrees… slow it down if you need to."
>
> FTE-1 stated that they had reached about 8 degrees of roll on that run. P-2 stated that he was trying to be "gentle with it as it started to go", because "directionally without the yaw damper its' really uh" (P-2 makes a side to side shaking gesture with his hand).
>
> P-4 advised P-2 that the maneuver had been performed too aggressively. P-2 stated that the 65 pounds of pull on the column was the same (as previously done) but with the improper trim setting, the pitch rate "came a lot faster." FTE-1 stated "you did what you were supposed to, it's just it's too much." P-2 said that he would do it slower, (apply the input to the control column slower) and P-4 reiterated that it had to be done slower.
>
> P-4 demonstrated an aggressive pull on the control column and stated "you take that thing and holding it, to me it's too aggressive, and you are pulling it up into a stall." FTE-1 agreed.
>
> P-2 practiced pulling back on the control column 4 four times at a slower rate. P-4 decided the next run would be an all engine operating takeoff with an EPR setting of 1.45, and he advised P-2 to "just pull it up to nine degrees….it doesn't have to be real fast….and you'll get a feel for it." He added "…we can't do that again, we can't have that… we can't pull it into a stall." P-2 "totally agreed." He said "I think we messed with the trim, which induced a different thing."
>
> P-4 stated that the trim was half a degree off, and that can change "it" a little but won't change it very much. He explained that he had experienced 1 degree differences in trim before and "it's like the CG is further aft." He showed P-2 the center of gravity envelope attached to the test cards and discussed it. He further explained that there is "a little less inertia, but the inertia is in the wings, but none of that matters you just have to accept the rate and you know if you get it mistrimmed a half a degree you can't crash the airplane. You've got to - got to stop the rate at 9 degrees" (Reference 29, pp. II-40-41).

Note that in this conversation, P-4 stated that "to me it's too aggressive and you are pulling it up into a stall," and "FTE-1 agreed." Furthermore, P-4's push on the control column to lower θ and α was essentially a stall-recovery maneuver, and prevented P-2 from "crash[ing] the airplane." Given this conversation, it is remarkable that P-4 and FTE-1 apparently later changed their minds, after they compared the predicted α_{stall} with the actual α achieved, and concluded that the roll-off was not due to a stall but to a lateral / directional disturbance associated with the unavailability of the damper (as discussed above in Section D-I).

Reference 29 indicates that following another takeoff (card 2A, performed with both engines operating), P-4 and P-2 continued the discussion about the rotation technique:

> At about 1407 GMT, P-4 briefed Card 3B2 for the next takeoff with a rotation to 9 degrees. He advised to do a control column input "just like that" as he demonstrated a column pull. "You don't have to do ah" (he demonstrated a more aggressive faster pull on the column). P-2 said that that he had been looking at P-3's control input technique all week "at that rate" and "kinda got that into my head." P-4 said "well, get it out." P-2 agreed, and said that he realized that he needed to slow it down, he just had to "deprogram" himself, but he understood and was working on it (Reference 29, p. II-45).

This exchange is consistent with TM-1's description of how the rotation technique developed by P-3 during flight 111 (and attempted on flight 132) was to be modified for flight 153, including a "slower pull" and a target pull force of 60-65 lb. rather than 70-75 lb..

The PE stated that the new takeoff technique developed during flight 111 in Birmingham succeeded in reducing the magnitude of the V_2 overshoots:

> The point of the Birmingham test was to refine our technique to get the target V_2 speed closer to what we were hoping to achieve. And during that technique, … we did -- after they hit a target pitch attitude for liftoff, they then pulled back further and increased the pitch attitude typically from 10 degrees up to 14 or 15 degrees during the climbout to 35 feet and we were able to achieve much lower V_2 speeds, probably only a few knots above our target as opposed to significantly more than that.
>
> … There were approximately six[38] runs conducted at Birmingham in mid-February and no roll-offs that I am aware of [Reference 23, pp. 14-15].

Note that while the V_2 speeds achieved using the techniques developed during flight 111 were reduced, they were still higher than the scheduled targets. P-3 told NTSB investigators that regarding these speeds,

> We didn't establish a tolerance. You know the target was to get on the speed. So we didn't say plus or minus 5 knots is acceptable. But the ones at Birmingham I think are probably the closest. We were getting I think around 3 knots or so within the V_2 but they were still all fast [Reference 30, p. 11].

Reference 29 suggests that FTE-1 may have been concerned about the status of the takeoff rotation technique, as of flight 132. Later in that flight, while P-2 was outside the cockpit, FTE-1 told P-4 that

> "I want to look at it and talk back to Savannah a little bit" (with regard to the data from the performance takeoff runs). He added "the thing is, this has got to be something I can have- the FAA can do, it can't be this hard a technique you know (the takeoff technique). If I can't train you guys to do it then-" (comment interrupted) [Reference 29, p. II-45].

The evidence presented in Reference 29 indicates that at the time of the accident, the test team had not yet succeeded in finding a takeoff rotation technique that would enable the airplane to capture the target speeds. The technique that had come closest to accomplishing this (developed by P-3 during flight 111) still resulted in V_{35} speeds that were high by about 3 knots, led P-2 to over-rotate and stall the airplane on flight 132, had not been demonstrated successfully on any performance takeoff following flight 111, and apparently caused FTE-1 to worry that it was too "hard a technique" for FAA certification pilots to accomplish. Furthermore, the technique itself was modified prior to flight 153, and so the technique prescribed for flight 153 was different from the one that had produced the best results on flight 111. Not surprisingly, throughout the morning of the accident the test team again resorted to iterative modifications of the rotation technique in attempts to capture the target V_2 speeds, as discussed further below. The difficulties the team encountered that day in capturing these speeds were exacerbated by the decision to reduce the target θ for flaps 10 takeoffs, but without (through an oversight) an accompanying increase in the scheduled takeoff speeds.

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[38] Seven takeoffs were performed at Birmingham on February 13, 2011, per References 28 and 29.

Reduction of flaps 10 target θ from 10° to 9°

The original θ target for the flaps 10 OEI CTO test was10°, and was later lowered to 9°. According to the PE,

> The 9-degree initial pitch attitude that was established as a flaps 20 target for Roswell II testing had its origins from the Birmingham flaps 20 OEI CTO testing conducted in Feb [2011]. This testing indicated that when an initial 9-degree pitch attitude was employed using our target rotation speeds, liftoff was generally occurring at or before 9 degrees.
>
> The initial 10-degree pitch attitude that was established as the initial flaps 10 target pitch attitude for Roswell II testing was based on the flaps 20 9-degree attitude plus a 1-degree increment to account for the expected difference in stall angles--flaps 10 vs. flaps 20. In general, the measured and estimated OGE and IGE stall angles for flaps 10 were about 1 degree higher than flaps 20. The rationale for applying this 1-degree shift in initial target pitch attitude is that if you want to employ the same V_2 stall speed criteria (1.13 V_{SR}) for both takeoff flap settings, you should operate at about the same [α] increments relative to the estimated stall angles. I am not aware of any further analysis which may have been conducted to show the flaps 10 target liftoff speeds with an initial pitch attitude of 10 degree were always less than the V_{LOmin} speeds for a 10-degree liftoff pitch attitude [Reference 27].

During their meeting on March 27, 2011, the PE and FTE-1 agreed to lower the target θ for flaps 10 from 10° to 9°. The reason for this adjustment is addressed on a slide titled "CTO Test Procedures" in Reference 21:

- Full Takeoff Thrust at Brake Release. Cut thrust to target EPRs on one or both engines well before target V_R
- At target V_R, pull on column to initiate rotation. Target max pull force of about 70 LB (60 to 65 LB for Flt 153)
- Rotate to target pitch attitude for liftoff
  - For OEI flaps 20, target pitch angle has always been 9 deg
  - For OEI flaps 10, target pitch angle was 10 deg prior to Flt 153. Higher pitch attitude flaps 10 due to higher stall angle flaps 10 vs flaps 20.
  - Just prior to Flt 153, adopted OEI flaps 10 9-deg pitch limit because of:
    - Overrotation abuse requirement and
    - Consistency with flaps 20
- After liftoff, adjust pitch to intercept target V_2, but not to exceed PLI (Pitch Limit Indicator)/shaker

The adjustment of the target θ for flaps 10 from 10° to 9° was requested by FTE-1. As further explained by the PE,

> The other thing [besides the V_{MU} data] that we discussed of significance [in the March 27 meeting] in hindsight was [FTE-1] asked me … if it was okay to use a 9-degree pitch attitude for the flaps 10 configuration. Because flaps 10 is not as important from a takeoff distance standpoint, I anticipated there may be a small performance penalty but I didn't consider that that significant for that configuration. So I mentioned to him that I personally had no problem with reducing the flaps 10 pitch attitude for liftoff from 10 degrees down to 9 degrees [Reference 23, p. 17].
>
> … [FTE-1 requested this change for] two reasons. There's an all engine abuse over rotation test that's required. And I guess the other issue that I've already mentioned is the flaps 10 data is not as limiting or is not as critical as the flaps 20, our primary takeoff consideration. So I think it was primarily the all engine operating 2-degree over rotation abuse case that he was concerned about. And the other thing was just consistency. We had already adopted the 9 degrees for flaps 20 and so what's the harm of using 9 degrees for flaps 10 as well. I think it was actually those two reasons [Reference 23, pp. 25-26].

As noted above, Reference 21 highlights that for a target θ of 10°, the scheduled V_{LO} speed of 132 knots for the accident conditions is 1 knot higher than the V_{LO} computed using the in-ground-effect C_L from Figure 2, but for a target θ of 9°, the scheduled V_{LO} speed is 4 knots below the V_{LO} computed using the in-ground-effect C_L. The significance of this difference is addressed in Reference 21 in a slide titled "Summary of V_{MU} Test Results:"

- Flaps 20 CTO target OEI takeoff speeds (V_R, V_{LO} and V_2) were valid for 9-deg pitch attitude at liftoff
- Flaps 10 CTO target OEI takeoff speeds were valid for 10-deg pitch attitude at liftoff
- Flaps 10 CTO target OEI takeoff speeds were too low for 9-deg pitch attitude at liftoff. Flaps 10 CTO target OEI takeoff speeds with 9-deg pitch attitude should have been increased by several knots

As explained further by the PE,

> What became an issue was the target speeds that we were using once we went to the 9° pitch attitude now put our liftoff speeds at essentially our target V_2 speeds and we were providing the flight crew with an almost impossible task to then pull back immediately after liftoff to hit the V_2 speed …[FTE-1] was not [aware of this issue] and we did not become aware of that … until the beginning of May. We finally got a copy of the draft V_{MU} report that [FTE-1] had been working on and once we got that report, we were able to go into the data had been reduced and determine that once the decision was made to reduce the pitch attitude for flaps 10 to 9 degrees, we should have gone back and adjusted our target speeds upward by approximately 4 knots, as I recall [Reference 23, pp. 18-19].

According to this statement, the speed schedule adjustments required to accommodate the lower θ target are determined using the C_L data shown in Figure 2, which are derived from an analysis of the V_{MU} tests. These results were not available to the G650 Performance Group prior to the accident flight, and so the Performance Group would not have been able to use them to make the required adjustments to the speed schedule. In regard to this problem, the PE stated

> It should be noted that the flight tested V_{MU} data referenced in this presentation[39] was not made available until after the Roswell accident, although it should have been possible to use estimated IGE (In Ground Effect) C_L vs [α] data from before V_{MU} flight testing to determine V_{LOmin} values as detailed in this presentation [Reference 28].

Regarding whether estimated IGE C_L data was in fact used to adjust any speed schedules, the PE stated

> I am not aware of any analysis that was done prior to working up target takeoff speeds for Roswell II that used estimated IGE lift curve data (C_L vs [α]) to determine V_{LOmin} speeds and then compared these minimum liftoff speeds to target liftoff speeds. Since [TM-1] and [another Performance engineer] worked up these speeds at the start of Roswell II testing, [TM-1] is in a better position than I am to comment on this question [Reference 27].

TM-1 stated

> The adjustment made between Roswell I and Roswell II for speed schedules was primarily to adjust rotation speed up by 2 knots as established during Birmingham testing for Flaps 20. Both the Flaps 20 and Flaps 10 speed schedules were adjusted to account for increase in 2 knots of rotation speed. There was no other adjustment made. I'm not aware of a predicted V_{MU} analysis being performed, I did not account for predicted V_{MU} [Reference 27].

The method for deriving takeoff speeds for the G650 based on the V/V_{SR} ratios for the G550 (described above) does not explicitly account for variations in the target θ for rotation. The target θ that corresponds to the speeds derived from the method was determined by

[39] The "presentation" referenced is Reference 22, which is an updated version of Reference 21.

observation of the results of the "parametric variations of rotation speed, rotation rate and climbout pitch attitudes" during the Roswell I tests, and on flight 111. Reconstructing the speed schedules across the whole T/W range to account for a different target θ therefore requires a different method than that used to obtain the original schedules. This alternative method, in turn, would have the C_L data shown in Figure 2 as its foundation:

> … the Gulfstream takeoff [computer] program … does not have the ability to determine different takeoff speeds as a function of target pitch attitude. To accommodate this it would be necessary to calculate V_{LOmin} values for a full range of takeoff values [using the V_{MU} results] and then divide these speeds by the reference stall speeds, V_{SR}, for these weights. Finally, these V_{LOmin}/V_{SR} values could be compared to the normal V_{LO}/V_{SR} values of the shifted GV data. If the V_{LOmin}/V_{SR} value is greater than the normal V_{LO}/V_{SR} value at a given T/W, the normal V_{LO}/V_{SR} curve should be shifted up to coincide with the V_{LOmin}/V_{SR} value. The corresponding normal V_R/V_{SR} and normal V_2/V_{SR} values should be shifted upward by this same $\Delta V_{LO}/V_{SR}$ increment. This method of adjusting takeoff speeds for use in the [Gulfstream takeoff computer] program for the most limiting constraints is detailed in the GVI Data Analysis Method, GVI-FT-003.[40] Hence, these adjustments are done outside the [takeoff computer] program. Only the final V/V_{SR}s that satisfy all certification criteria are input into the [takeoff computer] program to determine final AFM speeds [Reference 28].

V_2 overshoots and rotation technique development on previous flight 153 takeoffs

On the day of the accident, prior to the accident takeoff, the test team performed 11 other takeoffs at different flap and engine operating conditions. All of these takeoffs overshot the target speed at 35 ft. AGL by at least 4 knots, as indicated in Table 2:

Run	Config.: Flaps, engines	V_R			V_{LO}*				V_2§		
		Target knots	Actual knots	ΔV_R knots	Target knots	Actual knots	ΔV_{LO} knots	θ_{LO} deg.	Target knots	V_{35}† knots	ΔV_2 knots
2C1	F20 AEO	134	135	1		139		4.8	148	152	4
2C2	F20 AEO	134	135	1		140		5.3	148	156	6
2C3	F20 AEO	133	133	0		137		5.9	147	154	7
2C4	F20 AEO	133	133	0		138		5.8	147	153	6
3A1	F20 OEI	132	132	0	134	133	-1	4.2	136	142	6
3A2	F20 OEI	131	129	-2	134	130	-4	5.2	135	140	5
3A3	F20 OEI	131	130	-1	134	134	0	5.0	135	139	4
6C1	F10 AEO	130	132	2		137		5.3	148	158	10
6C2	F10 AEO	129	131	2		139		7.2	147	159	12
6C3	F10 AEO	128	129	1		141		8.7	146	153	7
7A1	F10 OEI	128	129	1	133	134	1	9.2	136	145	9
7A2	F10 OEI	127	127	0	132	132	0	11.2	135	-	-

Table 2. Flight 153 performance takeoffs (accident occurred on run 7A2).
*V_{LO} is identified by the start of the decay in wheel speed (see Reference 1, p. 12). Target V_{LO}s are provided for OEI runs only.
§For AEO takeoffs, the V_2 target listed is V_2 + 10 knots.
†V_{35} is the highest calibrated airspeed achieved between liftoff and a radio altitude of 35 feet, rounded to the nearest knot.

Plots comparing column force, column position, and pitch rate (Q) for each run corresponding to test cards 2C, 3A, 6C, and 7A are presented in Figures 9a through 12a. Plots comparing calibrated airspeed, pitch angle (θ), and radio altitude (h) for each run are presented in Figures 9b through 12b. The parameters are plotted as a function of time (t) elapsed from the start of the column pull to initiate rotation for each run. The L, R, and G symbols overlaid on the θ plots denote the t and θ values corresponding to the left and right weight-on-wheels (WOW) switches changing state (L and R symbols, respectively), and to the landing gear lever commanding gear up (G symbol). The different column inputs and resulting Q, θ, airspeed, and altitude profiles for each run can be discerned from these plots.

[40] Reference 20 of this *Addendum*.

As documented in Reference 29, the team started testing on flight 153 with card 2C, flaps 20 AEO CTOs. Before takeoff on run 2C1, P-2 asked "if we do an 11 degrees we're gonna abort, correct?" to which P-1 responded "yes" (Reference 29, p. II-52). This exchange echoes TM-1's report that during the pre-flight briefing the day before, P-1 and FTE-1 had agreed "that if they saw 11 or 12 degrees [of θ], it was a knock-it-off and recover maneuver."

The landing gear on run 2C1 was down for the time period plotted in Figure 9 (Reference 29, p. II-52), and so this should be kept in mind when comparing this run with the other card 2C runs, for which the gear was raised soon after the airplane was airborne. Extended landing gear will add drag, which will slow the rate of increase of the airplane's total energy.

On runs 2C2 and 2C4, the crew discussed the difficulty in maintaining V_2 + 10 knots at a θ of 20° or less.[41] After takeoff on run 2C4,

> P-2 said, "there's twenty." P-1 said "yeah, there's no way you're gonna maintain it within two knots, the plus ten, I mean we're up at 20 right now. That's what it is" [Reference 29, p. II-54].

This θ constraint (a GAC objective) appears to be in addition to the goal of capturing V_2 + 10 knots at 35 ft. AGL. Regarding the 35 ft. constraint, following the takeoff on run 2C3,

> P-1 said "The only thing I can say is you're not gonna be at 9 degrees very long if you want to catch V_2." FTE-1 replied, "yeah I agree, I think for the all engine that's kinda the case." P-1 said "It's like okay we're there and let's move on 'cause it's coming up, here it comes ready or not, 'cuz I'm still overshooting it" [Reference 29, p. II-54].

After run 2C4, the team moved to card 3A, flaps 20 OEI CTOs. Following the takeoff on run 3A1,

> P-1 noted that they would have to shoot for 15 or 16 degrees of pitch to capture V_2. He said that he was doing a nice smooth ramp, and "I'm not doing that jerk stuff, anyway it just doesn't work" (with regard to the initial input on the control column). He added "and that's not the way they're going to fly the airplane, and I don't think the FAA's gonna like it either…it's such a great flying airplane, you shouldn't have to abuse it to get the damn thing flying."
>
> FTE-2 reported that the force on the column was about 60 pounds. P-1 said "that works, that's comfortable." P-2 said "so a ramp to 60 worked pretty good."

As shown in Table 2, even though P-2 said that "a ramp to 60 [lb. column force] worked pretty good," the V_2 overshoot on this run was 6 knots. P-1's comments following this maneuver echo FTE-1's stated concern on flight 132 that abrupt column inputs with high peak forces made the takeoff technique too hard to be acceptable to the FAA. However, it was precisely the abrupt, "jerky" column inputs using high forces that enabled P-3 to reduce the V_2 overshoot to 3 knots on flight 111. Relaxing these inputs to something more "comfortable" would therefore likely result in greater V_2 overshoots (and longer takeoff distances). Following run 3A2, which was very similar to run 3A1 (see Figure 10), the conversation between FTE-1 and P-1 indicates that they were coming to the conclusion that to capture V_2, they would have to increase θ above the target of 9° earlier and earlier in the takeoff, until the increase in θ became almost "continuous:"[42]

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[41] The 20° θ limit is intended for passenger comfort during normal customer operations.
[42] Of course, another option was to come to the conclusion that the V_2 speeds were simply too low to be achievable using normal piloting technique. However, this option was not suggested by anyone on the test team.

> FTE-1 asked “is it taking it a while to accelerate up to V_2, I mean you’re holding that pitch I don’t know for a couple of seconds it looks like?” P-1 replied “oh no, I was trying to find it, no, it’s pretty – it’s pretty expeditious we’re blowing right through it again, even with one engine. I’m just trying to find what pitch I want to shoot for and it’s like 13, 14.” … FTE-1 said the ramp input was allowing P-1 to better hit the target pitch. P-1 said he had talked with P-4 about what technique he was using, and it sounded “pretty jerky. I mean he’d come back with it and jerk it forward… you are setting yourself up for bobble city with that one.”
>
> FTE-2 reported that the column force was 61.1 pounds. P-1 commented “ok that’s good. That’s all we need. I don’t think we need anything up around the seventies anymore, I think we’re done with that.” FTE-1 said, “the only thing I’m seeing is, is that when you pause at the pitch I guess you’re staying there a little while.” P-1 said “yeah, I need to just keep going with it. I mean, that’s the thing, we’re so intent on capturing that that I’m blowing through V_2.” FTE-1 said “yeah.” P-1 said “so, you know, it’s almost like a continuous maneuver.” P-2 echoed “it’s a continuous movement.” P-1 said “so, I think the idea is though, to get the pitch to get the airplane airborne.” FTE-1 said “right.” P-1 said “but it’s still blowing through V_2 and it’s just barely getting off the ground. I think it’s just what it is, apparently, the only thing we can fix that, we had a lot of conversations about that is… we talked about an earlier rotation or earlier liftoff, but I think that we’re about as slow as we want to go on that I think, unless we’re doing V_{MU} testing.”
>
> At about 0821 MDT, TM-3 asked if they were going to try it again and P-1 said yes. At about 0825 MDT, TM-3 said they were about 2 knots low on V_R and 3.5 knots high on the V_2. P-1 said “we’re not going to hang out long at 9, we’re just going to hit nine and then we’re gonna go for the 13 to 14 for V_2.” FTE-1 said “yep.” P-1 said “it’s almost a continuous maneuver.” He added that 3 knots above V_2 was not bad, because 2 knots was the criteria. The speed at 35 feet was critical. He said “nine degrees, based on that is a pretty good target…because that’s how they’re determining their distance” [Reference 29, p. II 57-58].

Figure 10a indicates that on run 3A3, P-1 pulled on the column more gradually and with less force than on runs 3A1 and 3A2, and achieved a peak Q of 5 deg./sec., compared to rates closer to 6 deg./sec. for the previous runs. As a result, θ increased to the target 9° more slowly on run 3A3 than on runs 3A1 and 3A2 (Figure 10b). However, on run 3A3 P-1 increased the pitch above 9° as soon as the gear was raised, about 1.8 seconds after the WOW indication.[43] This increase in θ occurred earlier in the takeoff than on runs 3A1 and 3A2; on run 3A1, the gear was raised about 3.8 seconds after the WOW indication, and θ did not increase above 9° until about 2 seconds later. On run 3A2, the gear was raised 2.5 seconds after the WOW indication, and θ did not increase above 9° until about 3.5 seconds later. Consequently, on run 3A3, θ increased above 9° about 3.5 seconds sooner (following the column pull) than on runs 3A1 and 3A2, and the V_2 overshoot was reduced (though V_2 still remained above its target; see Table 2).

After run 3A3,

> … FTE-1 said “I think that’s it.” P-1 said “we’re done, I think we caught it there.” FTE-1 said “yeah.” P-1 said “we must be onto something now.” FTE-1 said the airplane was “still pretty heavy” and he thought they would go for the flaps 10 maneuvers and “tomorrow we’ll go for score on it.” P-1 said he was happy with the nice smooth ramp input and 50-55 pounds force [Reference 29, p. II-58].

The team then moved to card 6C, flaps 10 AEO CTOs. In preparing for run 6C1,

> P-1 said this time he would rotate until the pitch reached 9 degrees, wait for a positive rate of climb, then capture V_2. He also said that more than 20 degrees of pitch would be required to maintain V_2 with both engines, but he liked the 9 degree pitch target and the rotation technique [Reference 29, p. II-58].

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[43] In the following discussion, “the gear was raised” refers to the movement of the landing gear handle to the “up” position (following which the gear will retract over about 7.4 seconds). The “WOW indication” refers to the latest time at which either the left or right WOW switch changed state from “on ground” to “in air.”

The plots of θ for the card 6C runs (Figure 11b) show a progression towards earlier and earlier θ increases above the 9° target, similar to the progression for card 3A (the flaps 20 OEI CTOs). On run 6C1, θ overshot the 9° target by about 1.5°, and then leveled out between 9° and 10° for about 3.7 seconds, increasing above 10° about 2.4 seconds after the gear was raised. On run 6C2, the 9° θ target was captured cleanly and held for about 3.5 seconds, increasing above 9° about 1.4 seconds after the gear was raised. The increase in θ above the initial target occurred about 1.2 seconds earlier on run 6C2 than on run 6C1; however, both runs overshot their V_2 + 10 knots target by at least 10 knots (see Table 2).

In between runs 6C1 and 6C2, "P-1 said 'you just can't do it within 20 degrees'" (likely referring to the θ required to maintain V_2 + 10 knots). He also said

> "so, TM-1 is saying we don't want to hang out at 9 degrees very long. Engine-out we gotta just keep it coming." P-2 said "we were just talking about it with (FTE-1). It's almost like it's just like a thought, a goal to go towards, but as soon as you get to it you gotta start pulling again to keep the speed down." P-1 said "yeah." P-2 said "it's like the aggressive pull." P-1 said "yeah." P-2 said "…and then the rest of it" [Reference 29, p. II-59].

During run 6C2, "P-1 said '…(looking for) V_2, well you can't really capture it here anyway, but that one (this run) that looked good to me." After landing and before run 6C3,

> … P-2 said "so which we wanna do next?" FTE-1 responded "well, we were pretty fast at 35 on that one, I'm not sure." P-1 said "yeah, it's got, there's almost ah- there's very little time at 9, you just gotta keep going, you wanna try one more and I'll just pause at 9 and just keep going?" FTE-1 concurred. P-1 said "I'll capture it and boom we're back into it. It's kinda what (TM-1) was saying * the data. Let's try another one….based on what I looked at with (TM-1), it's almost ah, you know it's almost a continual rotation. You can target 9, but you don't want to hang out there very long, because it's gonna blow right through it. So it's - now we're into kind of a technique thing here in how we're gonna do this."
>
> FTE-1 said "okay…that's what I was hoping, just spend today just to get something we like." The crew confirmed the airplane configuration, conditions and settings for the next run. FTE-1 said "…so we're targeting 146 (knots) at 35 (feet AGL)."

As shown in Figure 11b, the θ profile for run 6C3 is markedly different from that for any of the previous runs, but is very similar to the initial θ profile for the accident run (7A2), as will be discussed further below. Figure 11a shows that the general shape of the Q profiles for all 6C runs are similar between $0 \leq t \leq 3$ seconds, increasing to a maximum Q at about t =1.5 seconds, then falling back down to a low value by t = 3 seconds. However, the Q for run 6C3 does not reduce back to zero (as it does for runs 6C1 and 6C2), but after decreasing to 0.5 deg./sec. increases back to about 2.5 deg./sec. at t = 3.8 seconds. This Q profile is mirrored in Figure 11b in the slope of the θ curve for run 6C3, which only decreases, but does not flatten out, as θ increases through 9°. Indeed, θ only flattens out briefly at t = 4.8 seconds and θ = 11.5°, before increasing again. On this run, the gear was raised only 0.1 seconds after the WOW indication, compared to an interval of 1.3 seconds for runs 6C1 and 6C2. At the WOW indication, θ was 9.8° and Q was 2.4 deg./sec.. This performance is consistent with how P-1 and FTE-1 briefed the maneuver for run 6C3, and the resulting V_2 + 10 knots overshoot was reduced to 7 knots, compared to overshoots of 10 and 12 knots for runs 6C1 and 6C2, respectively (see Table 2).

During the discussion just prior to run 6C3, no one on the test team mentioned the agreement reached during the pre-flight briefing and confirmed earlier that morning that "if we do an 11 degrees we're gonna abort." Since at some point during the takeoff θ must increase above

11° to achieve the target V_2 speeds, and since the team was now discussing a "continual rotation," the circumstances under which a θ of 11° would require the maneuver to be aborted became more pertinent. Related to the significance of the 11° θ limit is the significance of the 9° θ target, and the team's understanding of the point during the takeoff beyond which this target could be exceeded.

NTSB investigators asked several GAC engineers and pilots involved with the G650 program what they understood the θ target to mean, and at what point it was permissible to exceed the target. As noted above, the PE indicated that the θ target constituted a limit while the airplane was on the ground, but after liftoff θ could be increased beyond the target: "You pitch-up to a certain attitude for liftoff but after liftoff, then you increase that attitude as you climb out" (Reference 23, p. 9).

TM-1 stated that, regarding the point in the takeoff at which the pilots could increase θ above the initial rotation target in order to capture V_2,

> That's not something I can speak to that is black and white. Essentially, we had discussions with the crew that once you lift off, start targeting that V_2 speed, but there was not a clear set of actions, I guess, defined by us. It was upon the – essentially upon the pilots to use their judgment as far as I know [Reference 32, p. 43].

Pilots P-3 and P-4 indicated that the initial target θ could be exceeded as required in order to capture V_2, without regard to whether the airplane had lifted off or not. P-4 stated that

> The pitch attitude was an initial pitch attitude to rotate the airplane to and then as the airplane accelerated the pitch was as required to intercept and maintain V_2 airspeed.
>
> … [the liftoff point] wasn't really part of the equation [Reference 12, pp. 9-10].

P-3 told investigators

> … you're targeting that initial 9 and then going for the speed target and then, of course, integrating that from the acceleration[44] and then you would just continue to pull the pitch to capture your V_2.
>
> … this technique is not only for the low altitude, low gross weight airplane where you have a really high acceleration rate, it's also for the high end hot conditions where your thrust of weight is greater, and in that case you may have to hold that initial target attitude for quite some time before you need to continue to increase pitch attitude to catch your V_2. So it just depends on acceleration rates and those characteristics that you are looking for.
>
> … [the liftoff point] has a lot more [relevance] now than what we had thought about, because the interpretation before [the accident] was it really didn't have [much relevance], using all of the numbers that we were given, it was supposed to just fall out. You know, it was to do the pitch rotate and then capture a V_2 speed.
>
> … [the new understanding is that liftoff] is important. You know the pilots did not specifically look for a liftoff point before continuing to do a pitch pull. Of course, now with all of the discussions on the detriment, the increased detriment of angle of attack than what was initially perceived, you know, that has more impact than what was initially thought. So there are more conditions. You know we have been educated more since then [Reference 30, pp. 27-29].

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[44] "Integrating from the acceleration" likely means correctly anticipating the increase in airspeed due to the airplane's acceleration so as to time the increase in θ such that the airplane reaches the correct trim θ just as the airspeed arrives at the desired trim value (V_2 for OEI, V_2 + 10 knots for AEO).

In the course of increasing θ to capture V_2, pilots attempt to keep θ below the Pitch Limit Indicator (PLI) on the Primary Flight Display (PFD), since the stick shaker will activate if θ reaches the PLI, and invalidate the run. As stated by P-3, during the takeoff

> … [we would] hold the target initial pitch attitude and then we would increase the pitch until we were able to capture V_2. What limited our pitch rate and the actual pitch value was the pitch limit indicator [Reference 30, p. 36].

Regarding how a pilot might identify the liftoff point, P-3 stated

> There are a couple of ways you can determine whether you have liftoff. One is … on the landing gear control panel there is a safety pin that will retract itself once the landing gear weight on wheels switches have gone to air mode. That way you know you have lifted off. Other than that there is really not one for a pilot unless he waits until he gets a positive climb indication. And that's the normal indication that you would use to raise the gear [Reference 30, pp. 30-31].

On flight 153, up until run 6C3, P-1's execution of the maneuvers was consistent with the PE's and TM-1's understanding concerning when θ could be raised above the initial 9° target. While in general the time intervals between the WOW indication and the raising of the gear, and between the raising of the gear and the increase in θ above 9° grew progressively shorter, in all but one case P-1 did not pull θ above 9° until after gear retraction (i.e., the airplane had lifted off). On the exception (run 2C4), θ was 9.3° and Q was about 1.5 deg./sec. as the gear was raised.[45] These trends are consistent with P-1 increasing θ earlier and earlier so as to minimize the V_2 overshoots, while keeping θ at the initial target until liftoff was indicated by P-2 raising the gear.

Run 6C3 was essentially different: P-1 increased θ above 9° *before* the WOW indication or the gear was raised. On that run, the WOW indication and gear retraction were nearly coincident, with θ at about 10° and Q at about 2.4 deg./sec. at the time. The execution of this run is more consistent with P-3's and P-4's understanding concerning when θ could be raised above the initial 9° target. The test team concluded from previous runs that a "continual rotation" was required to keep from overshooting V_2; and in fact, on run 6C3 the pitch rate was only reduced, not halted, when θ reached 9°, with the airplane still on the ground. This procedure reflects P-4's explanation that "the pitch was as required to intercept and maintain V_2 airspeed … [the liftoff point] wasn't really part of the equation."

Reference 29 states that regarding run 6C3,

> During the maneuver at rotation, P-1 said: "I'm going up, got 9, I'm going up, didn't stay there very long that time." FTE-1 said "yep." P-1 said "see what that does for us." FTE-1 said, "okay that's good." P-1 said "did you like that one?" FTE-1 said "well you didn't stay long, that was better on the pitch." P-1 said, "got nine and just continued on up."
>
> FTE-1 said "…you're six knots fast instead of ten, so that was a lot better. I think that's probably as good as it gets for that." P-1 said "could be, if you want any nine- if you want any pause at nine."
>
> TM-3 said: "speeds were better this time, pitch is a little high." P-1 said "(TM-3), we didn't pause very long at 9. we're trying to capture that V_2 at 35, so we're just, it's just not there very long, so. I think that's what you were seeing." FTE-1 said "that helps."

[45] However, on run 2C4 the WOW indication occurred 1.2 seconds before gear retraction, so the airplane had lifted off by the time θ increased above 9°.

> P-2 said “it’s really just becoming, I mean especially when it’s all engines, a 50 pound pull just to try to get the speed, to get the rate.” P-1 said “yeah, I don’t even have to think about it anymore, we don’t have to be jerking it off the runway or anything” [Reference 29, pp. II 60-61].

TM-3’s comment that “ … pitch is a little high” during this discussion is the closest any of the test team came to referencing the 11° θ value that they agreed earlier would result in aborting a maneuver. From the PE’s and TM-1’s understanding of the initial θ target (described above), and based on the execution of the runs prior to 6C3 in a manner consistent with this understanding, it is plausible that at least some of the test team understood the 11° θ limit in the same way as the PE and TM-1 understood the initial θ target: That these boundaries applied while the airplane was on the ground, but were no longer relevant once the airplane lifted off. From this perspective, since on run 6C3 the airplane lifted off and the gear was retracted while θ was less than 11°, the maneuver did not violate the 11° θ limit. Nonetheless, the timing was close: θ reached 11° about 0.5 seconds after liftoff. It is also noteworthy that the θ paused for about a second between 11° and 11.5° before increasing further.

After run 6C3, the test team moved to card 7A, flaps 10 OEI CTOs. The accident occurred on the second run of this test card (run 7A2). Runs 7A1 and 7A2 are compared in Figures 12a and 12b.

Figure 12b shows that on Run 7A1, θ was held at 9° until 1.5 seconds after gear retraction, and then increased to 14° as h reached 35 ft., about 8.5 sec. after liftoff. At that time, the airspeed had increased to 145 knots, 9 knots above the target V_2 speed of 136 knots (see Table 2).

Figure 12b also shows that the WOW indication did not occur on Run 7A1 until V reached 135 knots, 2 knots above the target V_{LO} and 1 knot below the target V_2. Identifying liftoff more precisely using the start of the decay of the main wheel speeds, the liftoff speed is 134 knots (see Table 2). In addition, θ reached the target 9° about 3 seconds before the airplane lifted off. On the previous takeoffs, the airplane lifted off before reaching the target θ (or, in the case of run 6C3, as it was increasing through the target θ), so in this regard run 7A1 was unique.

Reference 29 indicates that between Runs 7A1 and 7A2, the test team noted that V_2 exceeded the target during Run 7A1, but did not remark on the fact that the airplane attained the target θ 3 seconds prior to lifting off. Instead, the team discussed how the takeoff technique might be modified for the next run (7A2) in order to reduce the V_2 overshoot:

> After landing, P-1 said that they could try the same run again, using less of a pause while at the target pitch value. He said “it’s almost a continual maneuver then…I can do that, target nine and just keep going. I mean it’s I don’t know how else we’re gonna do it.” FTE-1 said “it seems like we were kinda hangin’ there for a little bit.” P-1 said “well we’re pausing, because we’re tryin’ to do this capture, and I think we’re getting too focused on that…. I think it’s a target, and then uh ‘cause if you have a real engine failure, the guys aren’t gonna be lookin at nine degrees, they’re gonna be lookin at tryin’ to get to V_2, they’re not gonna be payin’ any attention to that, so, that’s what I’m thinkin’. It’s an abnormal” [Reference 29, p. II-62].

This discussion mirrors the one that took place just prior to run 6C3, during which P-1 said “let’s try another one….based on what I looked at with (TM-1), it’s almost ah, you know it’s almost a continual rotation. You can target 9, but you don’t want to hang out there very long, because it’s gonna blow right through it.”

The θ behavior on run 7A2 is consistent with P-1's description of "almost a continual maneuver," "looking at trying to get V_2" and not "looking at nine degrees," other than "target nine and just keep going." A similar strategy was used on run 6C3, and on run 7A2, P-1 duplicated the pitch control inputs and θ profile used on run 6C3 very closely, as shown in Figures 13a and 13b. However, on run 7A2 he did not reduce the pitch rate as soon as on run 6C3, and as a result the θ for run 7A2 grew to be about 1° higher than that for run 6C3 after t = 3 seconds (see Figure 13b).

As described in the *Study* (Reference 1), on run 7A2 flow separation (stall) occurred on the right outboard wing as the airplane was lifting off, and as θ was increasing through 11.2°. The *Study* also notes that the right roll angle and roll rate present on run 7A2 contributed to the mechanism of the stall:

> The results of the CFD analysis, together with the nose-right sideslip angle, the reduced height of the right wingtip due to the right roll angle, and the increased α on the right wing due to the right roll rate, are consistent with a stall occurring on the right wing at about 09:33:50.5, as suggested by the simulation residual analysis [Reference 1, p. 34].

The roll angle and roll rate on run 6C3 (AEO) remained closer to zero than those on run 7A2 (OEI), and along with the approximately 1° lower θ, helped to keep the α across the span of the wing lower on run 6C3 than on run 7A2 (the maximum recorded α for run 6C3 is about 10.3°). Also, the airplane was about 2 ft. higher off the ground when θ reached 11° on run 6C3 than on run 7A2, which would have made $\alpha_{stall,IGE}$ somewhat higher on the former run.

The conduct and results of the takeoffs on flight 153 prior to the accident takeoff, and the discussions among the test team during and between these takeoffs, indicate that the V_2 overshoot problem remained unsolved. Further, the aggressive rotation technique developed by P-3 and FTE-1 during flight 111 to address the problem was unsatisfactory to P-1, even when the peak column forces were reduced from the 70-75 lb. pull used on flight 111 to the 60-65 lb. pull agreed to prior to flight 153. Throughout the morning of flight 153, the test team returned to an iterative approach to finding a rotation technique that would reduce the V_2 overshoots without resorting to "abusing the airplane" or "jerking it off the runway." This approach led to a more benign initial rotation, using a "nice smooth ramp" to 50-55 lb. of column force, and a "continual [rotation] maneuver" with only a reduction in Q as θ increased through the 9° target, without an attempt to "capture" the target. While on run 6C3 (flaps 10 AEO) this technique reduced the speed overshoot from 10 knots to 7 knots without stalling the airplane, on run 7A2 (flaps 10 OEI) θ was about 1° higher and, coupled with a slightly lower height and a right roll angle and roll rate, resulted in a stall of the right outboard wing.

Additional observations regarding the evolution of the takeoff technique on flight 153 are as follows:

- During the pre-flight briefing and prior to the first takeoff of the day, the test team agreed that "if we do an 11 degrees we're gonna abort." However, no one on the test team referenced the 11° limit again, even as the rotation technique evolved from capturing the 9° θ target to a "continual maneuver."

- The aircraft performance engineers' understanding of the significance of the 9° θ target apparently differed from that of the pilots. PE and TM-1 believed the target was a limit not to be exceeded until the airplane lifted off, while the pilots believed that the liftoff point "wasn't part of the equation."

- On run 7A1 the airplane reached the target θ about 3 seconds before lifting off, while on previous takeoffs the airplane lifted off before (or very close to) the time the target θ was reached.

- The test team appeared unaware of the θ required to trim the airplane at V_2 + 10 knots prior to flight 153, and only discovered through experience on that flight that it was not possible to trim at this speed within the desired θ limit of 20°.

- The difficulties in capturing V_2 on this and other flights appears to have been a problem unique to the G650 program. As such, it provided an indication that there might be fundamental problems in the assumptions underlying the target speeds.[46]

The course of events on flight 153, and in particular the iterative, "cut-and-try" approach to discovering both the airplane's takeoff rotation performance and dynamics, and the θ angles required to trim at the desired climb speeds, gave this test an aspect of exploration and discovery of the unknown, rather than one of verification and validation of expected results. The same can be said for the takeoff rotation technique development on flight 111 (which essentially carried over to flight 153).

These circumstances are likely related to the methods used to construct the takeoff speed schedules for the G650, which are based on a "similarity analysis" to the G550, but do not consider the dynamics of the rotation maneuver. Such similarity analyses are often used in preliminary design stages to size an airplane and to estimate its performance characteristics, but once the final design is complete, these estimates can be refined based on the actual aerodynamic, propulsion, and mass properties of the airplane. This refinement of the airplane's expected performance based on its actual physical characteristics can be fairly simple, based on an analysis of geometrical diagrams of the takeoff segments, or very sophisticated, based on three- or six-degree-of-freedom (DOF) simulations.[47] The next section describes some estimates of the rotation dynamics that can be gleaned from simple geometrical diagrams, and how simulation can be used to validate and refine these estimates.

Methods for predicting takeoff dynamics and validating takeoff speed schedules

Textbooks on airplane performance usually include a section about computing takeoff distance (see, for example, Reference 33). Typically, the takeoff is divided into four segments:[48]

- Ground roll
- Rotation
- Transition
- Initial climb (to obstacle height, = 35 ft. per FAR 25.113)

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[46] NTSB investigators asked several (eight) pilots, engineers, and managers at various levels within GAC if they had ever seen similar problems capturing V_2 on any other airplane (GAC or otherwise), and none of them had.
[47] 6-DOF simulations are described in the *Study* (Reference 1, pp. 24-25).
[48] Reference 33, Section 10.1, *Takeoff Analysis*.

These segments are illustrated in Figure 14. This *Addendum* will examine the pitch angle (θ), distance (S), speed (V), and altitude (h) relationships for the rotation, transition, and initial climb segments, since these are most relevant to the difficulties the test team experienced trying to achieve the G650 takeoff speed and distance targets.

This analysis starts with the assumption that a model of the airplane lift in ground effect, such as that described in Section D-I of this *Addendum*, is available. This model includes values for $(\partial C_L/\partial\alpha)_{IGE}$, α_0, and $\alpha_{stall,IGE}$. Presumably, V_{MU} and CTO test data will have been used to compute the values of k_h as a function of h_{MG}/b used to construct the model (see Figure 5).

The highest lift demand from the wing occurs during the transition segment in Figure 14, since during this segment $L > W$ in order to allow the airplane to trace the circular arc described by that segment. Accordingly, the highest α during the maneuver will occur during this segment. Assuming that the total lift in the segment remains approximately constant, the α will be highest where the speed is lowest, i.e., at liftoff. To keep this α (α_{LO}) comfortably below $\alpha_{stall,IGE}$, a stall margin $\Delta\alpha_{LO}$ (a negative number) is chosen, such that

$$\alpha_{LO} = \alpha_{stall,IGE} + \Delta\alpha_{LO} \tag{36}$$

This α_{LO} is the *highest* α intended for the rotation. Consequently, $\Delta\alpha_{LO}$ should be selected so as to keep α_{LO} low enough to avoid stall warning, even in the over-rotation abused takeoff case required by FAR 25.107(e)(4).

The minimum speed at which the airplane can lift off at α_{LO} is V_{LOmin}, for which $L = W$. To provide some additional lift capability to fly the circular arc shown in the transition segment illustrated in Figure 14, we would like to target a $V_{LO} > V_{LOmin}$. FAR 25.107(e)(1)(iv) suggests a speed margin to select here; the rule requires that V_{LO} be at least 105% of V_{MU} for the OEI case. Using a similar margin in this analysis, we can set[49]

$$V_{LO} = (1.05)V_{LOmin} \tag{37}$$

Where

$$V_{LOmin} = \sqrt{\frac{W}{\frac{1}{2}\rho C_{L,LO} S}} = \sqrt{\frac{W}{\frac{1}{2}\rho\left(\frac{\partial C_L}{\partial\alpha}\right)_{IGE}(\alpha_{LO}-\alpha_0)S}} \tag{38}$$

The transition segment ends with the airplane at the climb speed V_C, and at the θ required to trim at V_C (θ_C). This analysis assumes that the desired climb speed is that which yields the greatest flight path angle γ_C, which in turn results from flying at the α (α_C) that maximizes C_L/C_D. Thus

$$\theta_C = \gamma_C + \alpha_C \tag{39}$$

Where

$$\gamma_C = \sin^{-1}\left(\frac{T-D}{W}\right) = \sin^{-1}\left[\frac{T}{W} - \frac{1}{(C_L/C_D)_{max}}\right] \tag{40}$$

[49] One could of course choose a higher number, if more lift capability at liftoff is desired.

D is the drag force, and C_D the drag coefficient.[50] The climb speed V_C is approximately[51]

$$V_C = \sqrt{\frac{W}{\frac{1}{2}\rho C_{L,C} S}} = \sqrt{\frac{W}{\frac{1}{2}\rho\left(\frac{\partial C_L}{\partial \alpha}\right)_{OGE}(\alpha_C - \alpha_0) S}} \quad [41]$$

Where $C_{L,C}$ is the lift coefficient in the climb. Clearly, V and α will vary through the transition, since the beginning and end values of these parameters are different. Accounting for these variations precisely requires numerical integration over time, which is best accomplished using a simulator, as described further below. For this simple analysis, "effective" V_T and α_T values are used, assumed to equal the average of the beginning and ending values of these parameters:

$$V_T = \frac{1}{2}(V_{LO} + V_C) \quad [42]$$

$$\alpha_T = \frac{1}{2}(\alpha_{LO} + \alpha_C) \quad [43]$$

Assuming a relatively small angle for γ_C, the centrifugal force accelerating the airplane along the circular arc in the transition is $L_T - W$, where L_T is the lift force in the transition. Consequently,

$$L_T - W = \left(\frac{W}{g}\right)\left(\frac{{V_T}^2}{R_T}\right) \quad [44]$$

Where g is the acceleration due to gravity, and R_T is the radius of the circular arc transcribed by the airplane during the transition segment (see Figure 14). Dividing Equation [14] by W and recognizing that L/W is the normal load factor (nlf),

$$nlf_T - 1 = \left(\frac{1}{g}\right)\left(\frac{{V_T}^2}{R_T}\right) \quad [45]$$

$$R_T = \frac{{V_T}^2}{g(nlf_T - 1)} \quad [46]$$

Where $nlf_T = L_T/W = nlf$ in the transition. nlf_T can be expressed in terms of V_{LO}, V_C, $C_{L,C}$ and $C_{L,LO}$ (the C_L at liftoff) by recognizing that the lift in the climb (L_C) is approximately equal to W, and that per our assumptions, the C_L in the transition ($C_{L,T}$) is the average of $C_{L,LO}$ and $C_{L,C}$:

$$nlf_T = \frac{L_T}{W} = \frac{\left[\frac{1}{2}(C_{L,LO} + C_{L,C})\right]\left(\frac{1}{2}\rho {V_T}^2\right)S}{C_{L,C}\left(\frac{1}{2}\rho {V_C}^2\right)S} = \frac{1}{2}\left(\frac{C_{L,LO}}{C_{L,C}} + 1\right)\left(\frac{V_T}{V_C}\right)^2 \quad [47]$$

Substituting Equation [42] into Equation [47] gives

$$nlf_T = \frac{1}{8}\left(\frac{C_{L,LO}}{C_{L,C}} + 1\right)\left(\frac{V_{LO}}{V_C} + 1\right)^2 \quad [48]$$

---

[50] C_D is defined in Equation [23] in the *Study*.
[51] In the climb, the thrust vector has a vertical component, so lift is somewhat less than weight.

From Figure 14, the horizontal distance travelled in the transition segment is

$$S_T = R_T \sin \gamma_C \quad [49]$$

The height gained during the transition is

$$h_T = R_T - R_T \cos \gamma_C = R_T(1 - \cos \gamma_C) \quad [50]$$

If h_T ≥ 35 ft., then the climb segment is not required; of course, then the S_T calculated using Equation [49] needs to be recomputed using the γ_C that results in h_T = 35 ft., per Equation [50]. Also, some additional calculations to estimate the V at this point will be required, since V will not likely have reached the V_C assumed at the start of the analysis. These additional considerations are beyond the scope of the simple analysis outlined here.

If h_T < 35 ft., then the climb segment is required to account for the additional horizontal distance travelled while climbing to 35 ft. (S_C):

$$S_C = \frac{h_C}{\tan \gamma_C} = \frac{35\,ft. - h_T}{\tan \gamma_C} \quad [51]$$

Where h_C is the altitude gained during the climb segment.

There remains to estimate the distance travelled during the rotation segment (S_R), and a rotation speed V_R consistent with the desired V_{LO} and average pitch rate during rotation (Q_R). Q_R can be selected to be consistent with a “comfortable” rotation technique, using a “smooth” column pull to appropriate peak column forces (per P-1’s comments during flight 153, this peak force might be in the range of 50-55 lb.). The time (Δt_R) required to rotate to the liftoff pitch attitude ($\theta_{LO} = \alpha_{LO}$) is

$$\Delta t_R = \frac{\alpha_{LO}}{Q_R} \quad [52]$$

V_R can be estimated using Δt_R and the average acceleration during the rotation, $(dV/dt)_R$. This acceleration can be estimated from a calculation of the forces acting on the airplane (thrust, drag, and rolling friction), or from observations of actual acceleration from previous flight test takeoffs (in this case, from the Roswell I V_{MU} and CTO tests, for example). V_R can then be estimated as

$$V_R = V_{LO} - \left(\frac{dV}{dt}\right)_R \Delta t_R \quad [53]$$

S_R can then be computed from the average speed during the rotation:

$$S_R = \frac{1}{2}(V_R + V_{LO})\Delta t_R \quad [54]$$

The simplified analysis outlined above provides estimates of V_R, V_{LO}, and V_C (corresponding to V_2 for OEI takeoffs), and the distances required in the rotation, transition, and climb segments, while providing for:

- An adequate margin from stall during the rotation and transition segments, through a proper estimate of $\alpha_{stall,IGE}$ and selection of $\Delta\alpha_{LO}$
- A transition segment that ends with the airplane at the proper θ for trimmed flight at V_C
- A V_R that is consistent with arriving at the desired α_{LO} and V_{LO} using a "comfortable" rotation technique

The activity on flights 111 and 153 indicate that the test team was struggling to obtain satisfactory results in these three areas. Their difficulties stemmed largely from the fact that the method used to develop the takeoff speed schedules did not explicitly account for the geometry and dynamics of the takeoff maneuver as illustrated in Figure 14, and described above.

The analysis described above involves several approximations and simplifying assumptions, including the assumption of small angles for $\gamma_C$in modeling the dynamics of the transition, and the use of average αs, speeds, accelerations, and pitch rates in the transition and rotation segments. A much more exact calculation of the airplane's dynamics can be obtained through simulation.

As described in Section V of the *Aircraft Performance Study*, in a piloted simulation "a human pilot seated at the controls of a simulator cab makes control inputs as he would in a real airplane, and the simulation calculates the appropriate response in the control forces, airplane motion, instrument displays, and visual scene" (Reference 1, p. 24). "Desktop" simulations can be run without a pilot-in-the-loop, using computer code to drive the flight control inputs. For both piloted and desktop simulations, the response in the airplane motion is computed based on aerodynamic, propulsion, flight controls, and atmospheric models that define the forces and moments acting on the airplane at every moment, based on the airplane's state.[52] The simulation uses these forces and moments along with models of the mass properties of the airplane to solve the equations of motion and update the airplane's state through numerical integration.

The fidelity of a simulation is limited by the accuracy of its models. Before the airplane flies, these models may be based on a combination of information from empirical or theoretical estimates, models of similar aircraft, CFD solutions, and wind tunnel tests. After the airplane starts flight tests, the models can be updated based on recorded flight test data.

The takeoff speed schedules developed for the field performance tests could have been validated or "tested" using GAC's simulation of the G650 (this is the same simulation used to perform the "residual analysis" after the accident, as described in the *Study*). The piloted version of the simulation is referred to as the "Integrated Test Facility" (ITF). According to the PE, "to the best of my knowledge, we never attempted to demonstrate these maneuvers in the simulator prior to flight testing" (Reference 23, p. 49). However, TM-1 told investigators

> In the case of Flight 153, I do know that [FTE-1] and [P-2] went to the ITF simulator to basically work on, you know, the technique and kind of evaluate it prior to going out to Roswell. That's the only situation that I'm aware that there was practice, practice runs performed [in the simulator] [Reference 32, p. 49].

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[52] The airplane "state" refers to its motion parameters, including its position, orientation, and linear and angular speeds and accelerations. It can also refer to the condition of airplane subsystems, such as flight control surface positions, flap and landing gear configuration, etc..

TM-1 also indicated that FTE-1's and P-2's work in the ITF may have influenced the reduction in the target column pull from the 70-75 lb. used on flight 111 to the 60-65 lb. agreed to prior to flight 153 (Reference 32, p. 9).

P-3 indicated that one reason that the ITF was not used to validate the takeoff speeds is that its fidelity was perceived to be poor:

> As I mentioned the fidelity [of the ITF] was poor. I don't know even on the initial that we utilized it at all. When [P-1] and I first went out we used the basic airplane and used the buildup. So we used it [the airplane] as our device for getting airplane characteristics.
>
> … [the ITF was not used as a predictor because then] you would train to something that wouldn't really happen in the airplane. So it's almost like it's adverse feedback [Reference 30, pp. 93-94].

As discussed in the next section, since the accident GAC has re-computed all of the takeoff speeds for the G650 using a method based on the simulation underlying the ITF. GAC updated the simulation models used to accomplish this work based on knowledge of the G650 ground effects gained from GAC's CFD studies conducted after the accident. While these updates certainly improve the fidelity of the simulation, it is probable that the fidelity of the models even prior to the accident was sufficient to identify and investigate the difficulties associated with the rotation technique, overshooting the V_2 speeds and takeoff distances, and trimming the airplane within the desired 20° θ limit.[53]

While discussing the development and validation of the takeoff speeds, the PE told investigators

> For the ground [roll] portion [of the takeoff] we used first principles F=ma analysis. For the rotation and air segment phases we simply used estimated V/V stalls that we had gotten from the GV and shifted them down to the target speeds that we were trying to hit on the G650 but we had also adjusted those schedules slightly based upon some experience that we had gained during Birmingham testing in February of 2011.
>
> … In hindsight looking at the data if we had a at least full degree of freedom, 3 degree of freedom dynamic program that would have been very useful in gaining further insight into speeds and conditions for the takeoff maneuvers. And from our own internal investigation at review of the incident I think we have decided that that is a very beneficial option that we need to take that we did not.
>
> … you know, the most recent programs really we were dealing with derivatives of existing programs. The G550 was a derivative of the GV. So there we already had our, there were few, if any, changes between the two airplanes so using the GV CTO data was a very natural thing. The G450 derivative of the GIV using that data was a very natural thing.
>
> As you move off to new aircraft design one of the big lessons learned from this is that you probably want to do a more in-depth 3 degree of freedom analysis to get better insight into all of the critical parameters that are involved in CTO performance. And I think in fairness it takes -- we have been working months to fine tune our ITF analysis to make that match up. And it takes a lot of upfront work to program everything to get that. And so that was because of the effort involved that was not undertaken in the 650 program [Reference 24, pp. 44-45].

Regarding modeling the airplane prior to flight testing, the SSAA told NTSB investigators that

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[53] GAC personnel did not indicate that an investigation of the takeoff speeds and rotation technique using the ITF had in fact been attempted, but found wanting because of poor correlation to flight test data. In any case, P-2 and FTE-1 apparently found it worthwhile to "practice" in the ITF prior to flight 153.

> Usually in a program, I mean, when you come up with an estimate or something to that effect, in this case, speeds, you usually have a tool to model the physics of the takeoff and it could be a super sophisticated simulation but you can get away with it with something to be a lot less aggressive, something like a 2 or 3 degree of freedom model. And using that model, if you can develop a set of speeds, you should be able to check those speeds out on that model and see whether or not they're achievable.
>
> And then I would think the next progression would be to go from that model to a simulator and see if the pilot can fly. If the pilot can't fly them, then you go back and adjust your model. If the pilot can fly them, then you take them out and test them [Reference 8, pp. 29-30].

The SSAA also described the approach to field performance flight testing used when he was involved with such work on programs outside of Gulfstream:

> In general, we're all using some kind of a desktop calculation. You use that tool to develop your speeds and to show that the aircraft takes off, safely takes off and gets to 35 feet and you usually set up the data, which is your reference speeds from those calculations and that's what you use to perform the tests.
>
> You would go into the testing -- if you had a simulator, you would probably put the pilot on the simulator and let him give you an indication of whether those speeds were achievable. When you went to the testing, you would usually provide some method of stepping down to those speeds. …
>
> And you would be always looking to correlate that field performance against what your predictions were. The beauty of that method is that you can use everything that's flying. You don't have to discard points because the pilot overshot or you think you can come back glean a lot of information out of it and then you adjust your model to match those speeds and your model should be within a certain estimate or certain range of values of what flight tests are showing. And then once you've got that correlation, then you expand that data to generate your field performance for your AFM [Reference 8, pp. 37-38].

Regarding what he discovered (after the accident) regarding the approach to field performance flight testing taken on the G650 program, the SSAA stated that

> I was surprised that there was no desktop calculation to verify speeds. I was surprised that the dynamic part of the maneuver was modeled by average speeds over timeframe and not an integration of a differential equation. I was surprised that they went and tested those speeds at the value that they were calculated at and didn't come down in speed. It seemed like we had a set of speeds and we know the theoretical basis and then we went straight into flight tests with them. In other words, we were using hazardous testing to extract data which is the wrong way to go on any testing. If you go back to the point where you look at performing a test, a department will request a set of testing. They should have some estimates of how the aircraft is going to perform and the flight testing is just a verification of that data. If it doesn't verify the data, then you stop and you adjust your model or you see what is going on with your model [Reference 8, pp. 38-39].

Since the accident, simulation and modeling has assumed a very prominent role at GAC in the development and validation of takeoff speeds, and in the conduct of field performance flight tests. These developments are described in the next section.

IV. GAC post-accident actions regarding takeoff speeds development and testing

GAC "white paper"

Appendix B of this *Addendum* is a "white paper" produced by GAC, at the invitation of NTSB, describing the changes the company has made since the accident regarding takeoff airspeed development and testing. The methods described in the *Improved Methodology for Take-off Performance Development* section of Appendix B are founded on simulation and modeling, and indicate that the benefits of these tools, as described above by the PE and SSAA, are now in place to support takeoff speed development at GAC.

Specifically,

> The new method proposed at Gulfstream for airspeed development does not employ legacy airspeed data, but instead generates airspeeds using a 3 degree of freedom desktop simulation that represents the dynamics of the maneuver, the aerodynamics of the aircraft in and out of ground effect, and the control effectiveness present in a particular aircraft. This desktop simulation has been developed to more precisely model the take-off maneuver and predict representative take-off safety speeds. … the program is used to develop a set of take-off speeds that ensure, among other considerations: 1) an achievable and repeatable initial pitch attitude is ensured at rotation and 2) a suitable margin between the operating angle of attack and the stall angle of attack during ground effect operations and climb out to obstacle clearance height [Appendix B, p. 3].

In addition, pilot-in-the-loop simulations in the ITF are now used to verify an acceptable takeoff rotation technique:

> The ITF is now being employed in a dual role to help in the development of the G650 take-off speeds. The first is the development and verification of a suitable and repeatable pilot technique, which allows the aircraft to safely rotate to the initial pitch attitude and to lift-off and climb-out through obstacle clearance height without requiring exceptional pilot skill. In this capacity, a technique was developed, tested and verified using multiple Gulfstream pilots and several FAA pilots performing controlled all-engine and single engine take-offs using this pilot-in-the-loop simulation in the safety of a laboratory environment before migrating the technique onto the flight test aircraft [Appendix B, p. 3].

Simulation is also used at the flight test site itself to provide

> … improved real-time monitoring and analysis of the general handling characteristics of the aircraft during all phases of the take-off testing. … engineers utilize two dissimilar real-time desktop simulations to predict the aircraft characteristics for each maneuver being flown and provide the expected minimum margins to aerodynamic stall. Prior to the start of each take-off run, estimates of the minimum margins are developed by each simulation, compared for validity, and properly communicated to the crew on the test aircraft before the aircraft is released for take-off. As an additional level of safety, a build-down to the published take-off speeds during the initial phase of each take-off test was implemented. If during this phase the aircraft shows abnormal handling qualities, reduced acceleration during the ground roll and/or excessive air phase or climb out times than predicted by the on-site desktop estimates, testing shall be halted and the data thoroughly reviewed. If the cause of any abnormal characteristics cannot be immediately identified and corrected, testing shall be halted until the phenomenon is satisfactorily explained [Appendix B, p. 4].

GAC has also used the results of the CFD ground-effect study (described in Reference 1) to update flight test methods and instrumentation, both on the airplane and in the telemetry trailer:

> Initially, this information was used to more precisely define takeoff speeds and later was employed to generate safety of flight angle of attack margins to be used in flight testing. These are monitored in real time both on board the aircraft as well as by a ground support crew of engineers in the telemetry trailer. As an effort to improve safety and pilot awareness, a flight test aid was developed in the Flight Control Computer (FCC) utilizing the G650 radio altimeters to indicate height above the ground. By knowing the height above the ground and air data Mach number, ground effect stall angle can be computed. Combining this with a suitable margin to stall, the FCC can drive the pitch limit indicator (PLI) on the attitude indicators on both the primary flight display (PFD) and the heads up display (HUD) providing the pilots with an unprecedented level of ground effect situational awareness. Lastly, in the event the aircraft angle of attack encroaches upon this margin to stall, the FCC will then activate the stall warning stick shaker [Appendix B, p. 4].

Appendix B also presents updated takeoff speeds for the G650 resulting from the new takeoff speed development and testing methods just described. The changes in the speeds for the accident conditions (at the 87000 lb. weight used by the crew) are summarized in Table 3:

Speed	Value for flight 153 Run 7A2 (accident) knots	New value knots	Δ speed knots	% difference
V_R	127	137	10	7.9
V_{LO}	132	140	8	6.1
V_2	135	150	15	11.1

Table 3. Updated flaps 10 takeoff speeds for the accident conditions and 87000 lb. gross weight.

Interestingly, the 11.1% increase in V_2 shown in Table 3 correlates well with the 11.9% increase in V_2 that Equation [33] indicates would result from using the $\Delta\alpha_{margin}$ and the regulations (multipliers on V_{SR}) that were used on previous GAC models.

E. CONCLUSIONS

This *Addendum to the Aircraft Performance Study* examines several topics relevant to the field-performance flight-testing during which the accident occurred. These include evidence available at the time of the accident regarding the airplane's actual stall angle of attack in ground effect; the methods used by GAC to generate and validate takeoff speed schedules for field performance testing; the difficulties the test team encountered achieving the scheduled speeds, and their attempts to overcome these difficulties; and the changes GAC has made to its methods for takeoff speed development and validation since the accident.

The information presented in this *Addendum* indicates that at the time of the accident, the flight test data collected by GAC during previous performance takeoffs of the G650 was sufficient to quantify the changes in lift due to ground-effect. In particular, the wing-drop events on flights 88 and 132 provided evidence that the actual decrement in the stall angle of attack due to ground effect was larger than what had been assumed. However, while a limited audience in the flight-test community was briefed about the flight 88 event, the flight 132 event was not briefed beyond the flight crew involved, who misdiagnosed the event as a lateral-directional upset influenced by the unavailability of the yaw damper, rather than as a stall event. Furthermore, GAC did not perform an analysis of either the flight 88 or flight 132 events to determine their root physical causes until after the accident, even though such analyses had been performed following similar events on previous airplane programs.

The investigation also revealed that the takeoff speed schedules developed for the field performance tests were built around a decision to make the airplane's V_2 speed identical to the minimum V_2 allowed by the FARs. In addition, amendments to the FARs prior the start of the G650 program changed the definition of the stall speed, and reduced the multipliers on the stall speed used to determine the minimum V_2 speed. As a result, during field performance takeoff tests the airplane was being operated with smaller margins to stall than on previous GAC airplane programs. At the same time, the V_R and V_{LO} speeds were computed based on a "similarity analysis" to the G550 airplane, using increments from V_2 (normalized by V_{SR}) derived from similar normalized increments for the G550. This method differed from that described in GAC's *Model GVI Data Analysis Methods* document. In addition, GAC did not perform any dynamic analysis or simulation modeling of the takeoffs prior to field performance flight tests to validate the resulting takeoff speeds, or determine if they were achievable.

Throughout field performance testing, the airplane consistently "overshot" the desired V_2 speed (or V_2 + 10 knots, for AEO takeoffs) at 35 ft. AGL. Following the first round of field performance testing in Roswell in November 2010, test crews attempted, through an iterative approach, to find a takeoff rotation technique that would enable the airplane to capture the desired speeds at 35 ft. AGL. A rotation technique employing an abrupt column pull of over 60 lb. was found to reduce the magnitude of the speed overshoots, though it did not completely solve the problem. Additionally, members of the test team were concerned that the new technique involved "abusing" the airplane and "jerking it off the runway," and may therefore have not been acceptable for FAA certification.

Prior to the accident flight, GAC engineers reduced the flaps 10 target pitch angle for takeoff rotation from 10° to 9° to accommodate abused takeoff requirements, and to provide a consistent pitch angle target for both flaps 10 and flaps 20. However, the flaps 10 takeoff speed schedules were developed for a target pitch angle of 10°, and through an oversight, were not adjusted upwards as necessary following the lowering of the pitch target to 9°. The method used to generate the original speeds did not explicitly account for the target pitch angle, and the V_{MU} test results necessary to make the proper speed adjustments had not been fully processed prior to flight 153. The change in the target pitch angle (without a corresponding increase in speeds) exacerbated the difficulty in capturing the target speeds for flaps 10 takeoffs.

On the day of the accident, the test crew was again exploring takeoff techniques to solve the speed overshoot problem using an iterative approach. In an attempt to keep the speed down, over the course of the morning, the crew used progressively briefer “pauses” at the target pitch angle of 9° before increasing the pitch angle further. On the accident takeoff, there was no pause at 9° at all, but only a slowing of the pitch rate, as the airplane pitched through 9° and then stalled at a pitch angle of approximately 11.2°. The stall occurred about 1° below the PLI limit, and prior to stick shaker activation.

In the time since the accident, GAC has updated its takeoff speed development and testing methods to use simulation and modeling as their foundation. Simulations are used to compute appropriate takeoff speeds and ensure that they provide adequate margins to stall throughout the takeoff maneuver; to develop and validate rotation techniques through pilot-in-the-loop simulation; and on-site during field performance testing, to predict airplane performance prior to each run for real-time comparison with actual performance. The V_2 speed for the accident conditions derived using the updated methods is 15 knots (11%) faster than the V_2 speed used by the test crew on flight 153.

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Office of Research and Engineering

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G. GLOSSARY OF SYMBOLS AND ACRONYMS

English characters

AC	Advisory Circular
ADC	Air Data Computer
ADS	Air Data System
ADSP	Air Data SmartProbe
AEO	All Engines Operating
AFM	Airplane Flight Manual
AGL	Above Ground Level
b	Wingspan
$\hat{c}$	Mean aerodynamic chord
CFR	Code of Federal Regulations
CFD	Computational Fluid Dynamics
CG	Center of Gravity
C_L	Lift coefficient
C_N	Yawing moment coefficient
C_R	Rolling moment coefficient
CVR	Cockpit Voice Recorder
D	Drag force
DOF	Degree(s) of freedom
EMS	Rolls Royce Deutschland Engine Monitor System
$\vec{F}$	Force vector
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FCC	Flight Control Computer
FDR	Flight Data Recorder
FR	Heim Flight Recorder
FS	Fuselage Station
FTE	Flight Test Engineer
FTIS	Flight Test Instrumentation System
$\vec{g}$	Gravity vector
g	Acceleration due to gravity (32.17 ft/s^2)
GAC	Gulfstream Aerospace Corporation
h	Altitude or height above the ground
HIPF	High Incidence Protection Function
IGE	In-ground-effect
IRS	Inertial Reference System
ISA	International Standard Atmosphere
ITF	GAC Integrated Test Facility
KCAS	Knots calibrated airspeed
KROW	Roswell International Air Center Airport
L	Lift force
m	Airplane mass = W/g
M	Pitching moment
$\vec{M}$	Moment vector
N	Yawing moment
OGE	Out-of-ground-effect
MAC	Mean Aerodynamic Chord
MDT	Mountain Daylight Time
MFP	Multi-function Probe
MSL	Mean Sea Level
$\vec{n}$	Load factor vector
nlf	Normal load factor = $-n_z$
NAOA	Normalized Angle of Attack
NTSB	National Transportation Safety Board
PF	Pilot flying
PFD	Primary Flight Display

PIC	Pilot-in-command
PLI	Pitch Limit Indicator
PM	Pilot monitoring
$\bar{q}$	Dynamic pressure
Q	Body-axis pitch rate
R_T	Radius of circular arc of takeoff transition segment
S	Wing area
SAT	Static Air Temperature
SIC	Second-in-command
TAT	Total Air Temperature
t	Time
T	Thrust
TSHA	Test Safety Hazard Analysis
u	Velocity component along x-body axis
USGS	United States Geological Survey
UTC	Universal Coordinated Time
v	Velocity component along y-body axis
V	Total velocity (inertial speed or airspeed dependent on context)
$\vec{V}$	Velocity vector (inertial speed or airspeed dependent on context)
V_1	Takeoff decision speed. V_1 means the maximum speed in the takeoff at which the pilot must take the first action (e.g., apply brakes, reduce thrust, deploy speed brakes) to stop the airplane within the accelerate-stop distance. V_1 also means the minimum speed in the takeoff, following a failure of the critical engine at V_{EF}, at which the pilot can continue the takeoff and achieve the required height above the takeoff surface within the takeoff distance.
V_2	Takeoff safety speed
V_{35}	Speed at 35 ft. AGL ("screen height")
V_{EF}	Engine failure / throttle chop speed for OEI takeoffs
VFR	Visual Flight Rules
V_{LO}, V_{LOF}	Lift-off speed
V_{MC}	Minimum control speed
V_{MCA}	Minimum control speed in air
V_{mu}, V_{MU}	Minimum unstick speed
V_R	Takeoff rotation speed
V_S	Stalling speed
V_{SR}	Stall reference speed
w	Velocity component along z-body axis
W	Airplane weight = mg
W_{LO}	Weight at lift-off
WOW	Weight-on-wheels
x	x-coordinate (axis system dependent on context)
y	y-coordinate (axis system dependent on context)
Y	Side-force
z	z-coordinate (axis system dependent on context)

Greek characters

α	Angle of attack
β	Sideslip angle
γ	Flight path angle
Δ	Increment or difference in the quantity following the Δ
θ	Pitch angle
ϕ	Roll angle
ψ	Heading or track angle (magnetic or true dependent on context)
$\vec{\omega}$	Rotational velocity vector
ρ	Air density

FIGURES

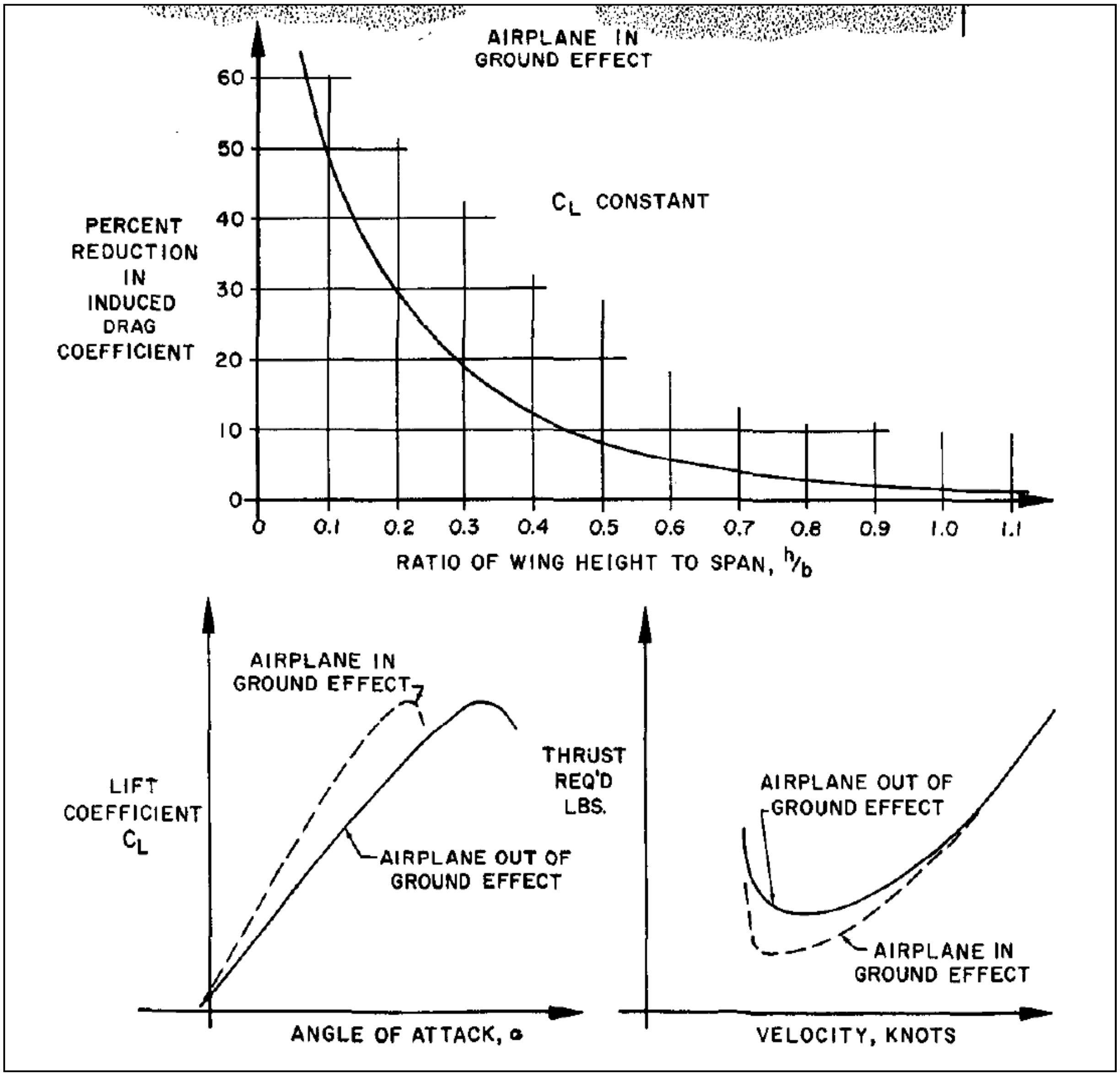


Figure 1. Ground-effects on airplane aerodynamics (from Reference 2)

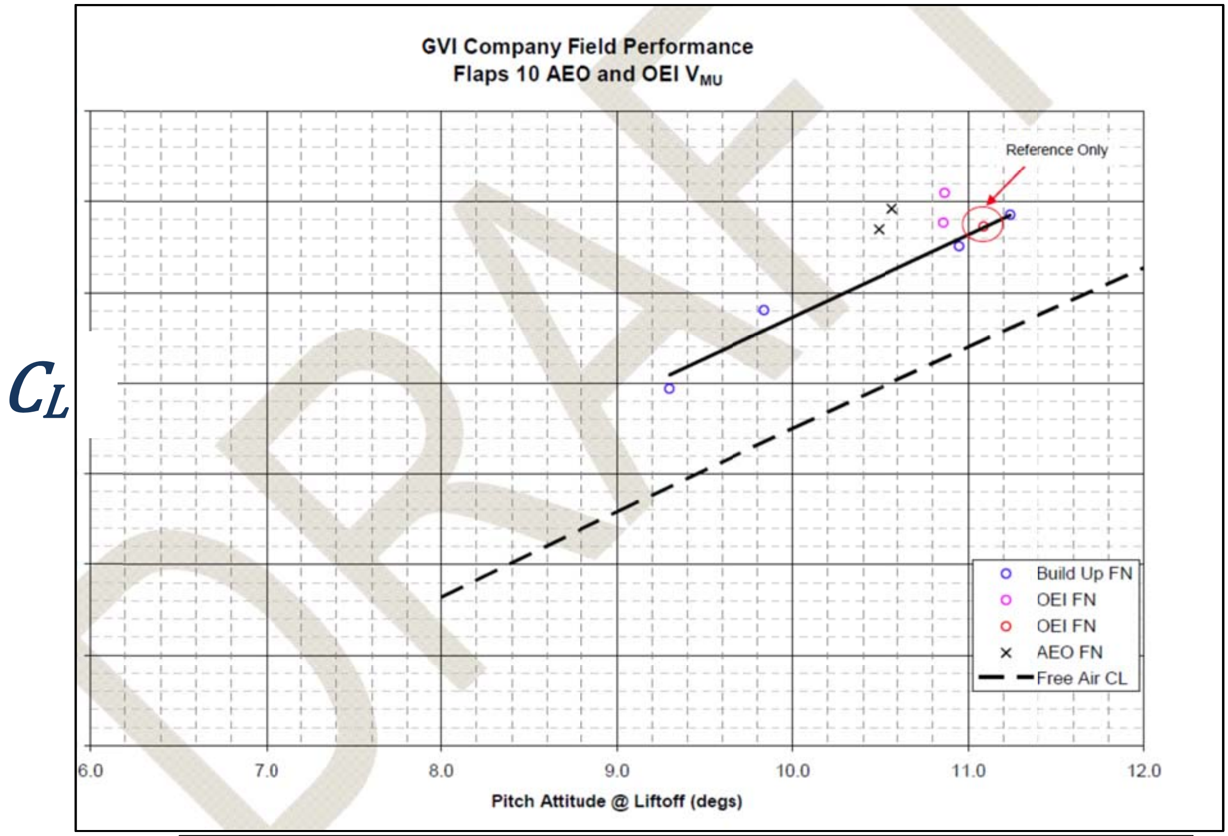


Figure 2. Figure 2 from Reference 6: Flaps 10 Pitch vs. Lift Coefficient.

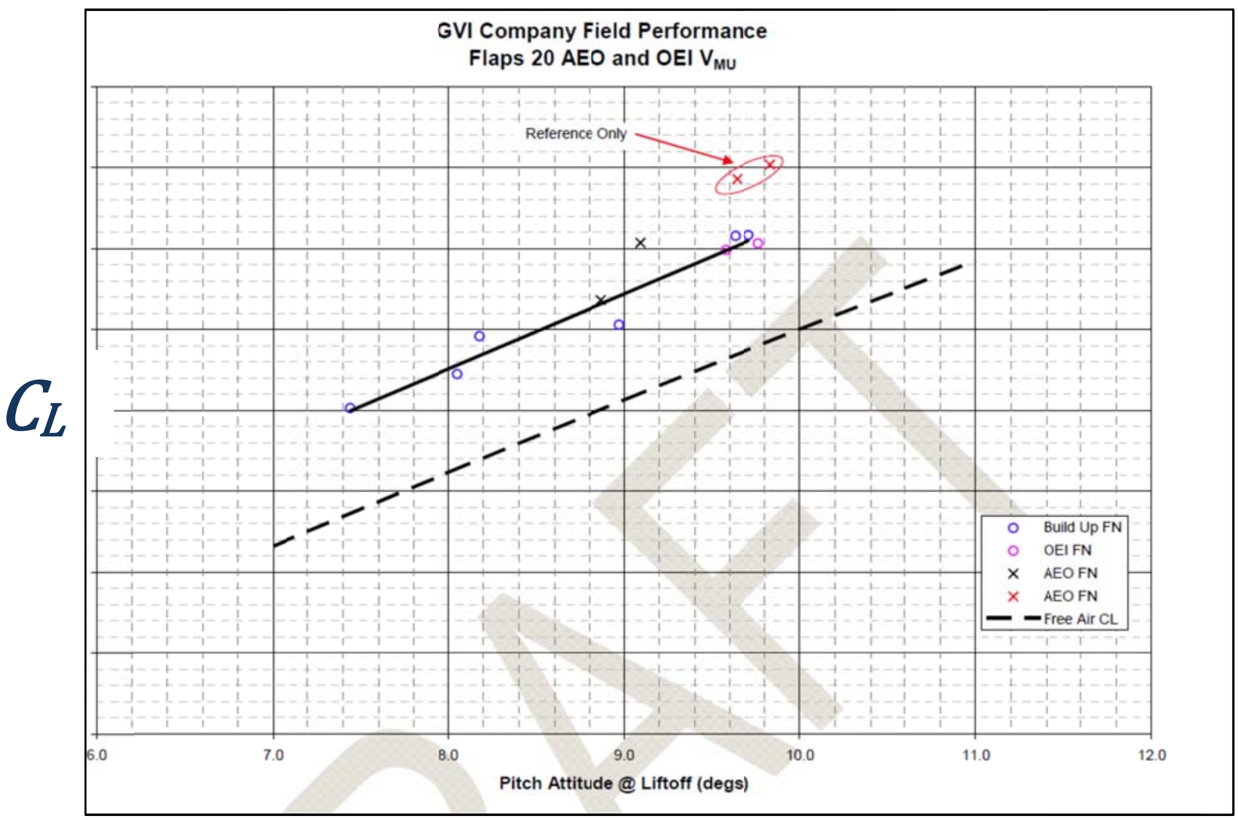


Figure 3. Figure 4 from Reference 6: Flaps 20 Pitch vs. Lift Coefficient.

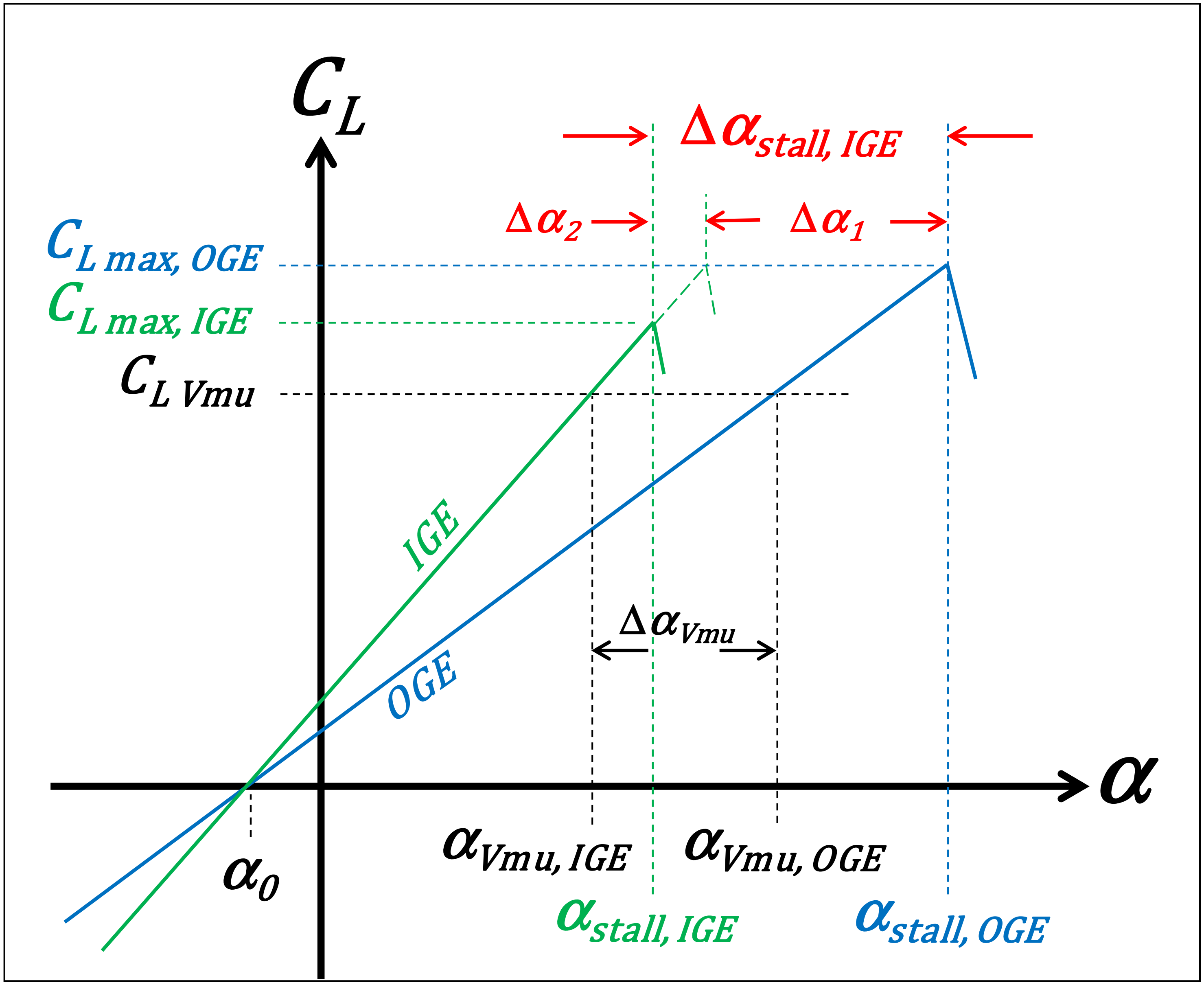


Figure 4. Model of lift in ground-effect.

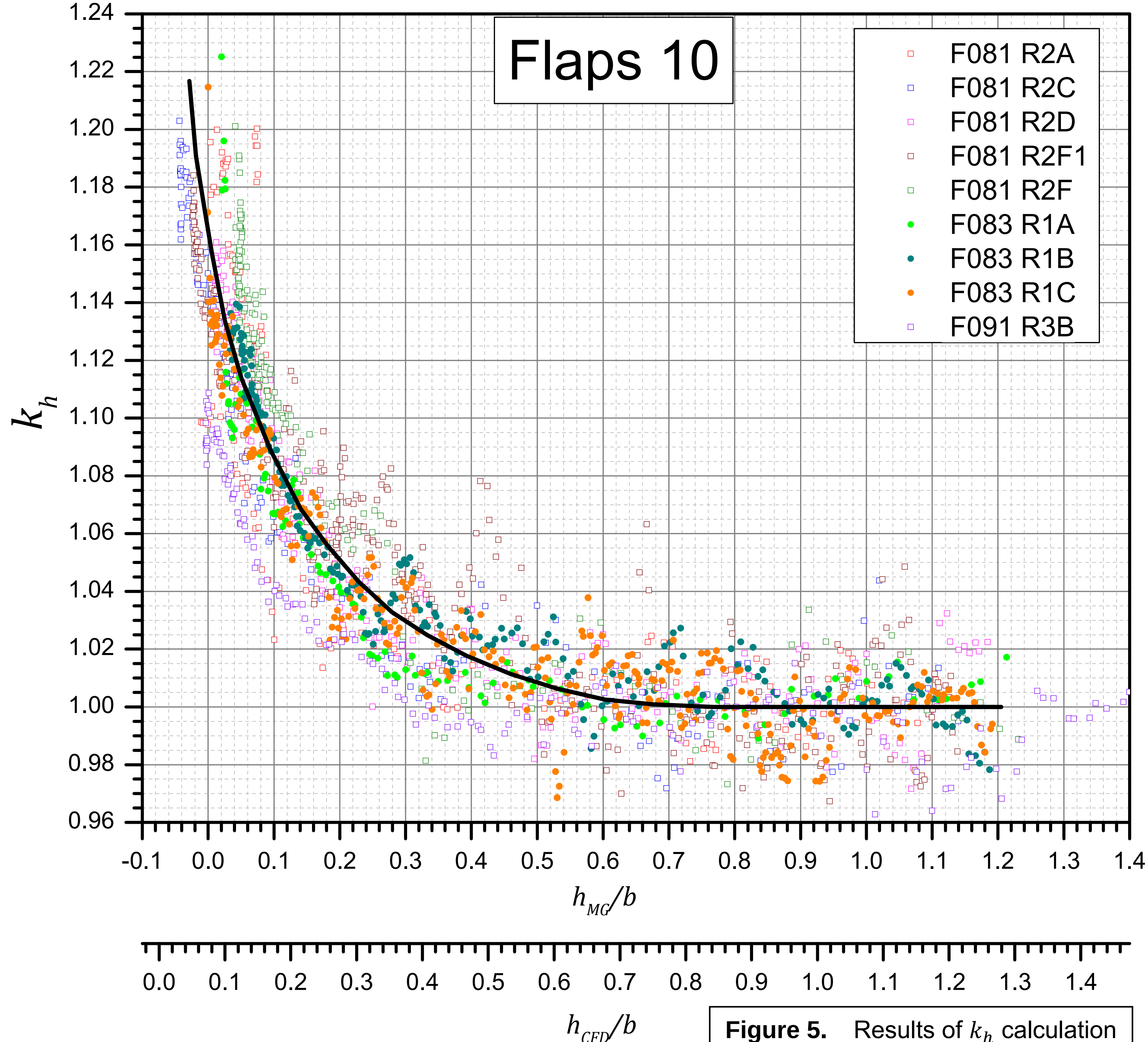
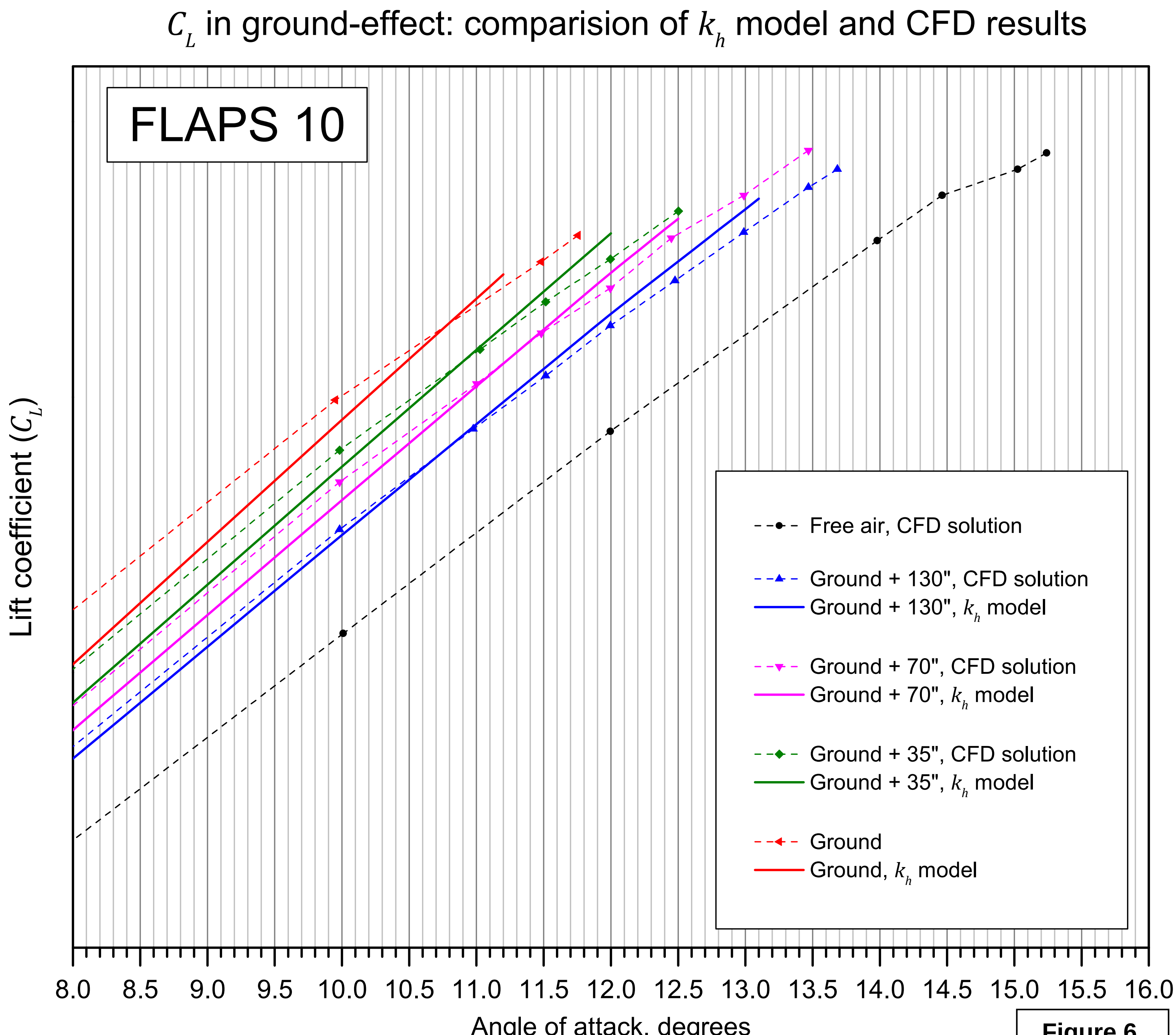


Figure 5. Results of k_h calculation for flaps 10.



C_L in ground-effect: comparision of k_h model and CFD results
FLAPS 10
Lift coefficient (C_L)
8.0 8.5 9.0 9.5 10.0 10.5 11.0 11.5 12.0 12.5 13.0 13.5 14.0 14.5 15.0 15.5 16.0
Angle of attack, degrees
Free air, CFD solution
Ground + 130", CFD solution
Ground + 130", k_h model
Ground + 70", CFD solution
Ground + 70", k_h model
Ground + 35", CFD solution
Ground + 35", k_h model
Ground
Ground, k_h model

Figure 6.

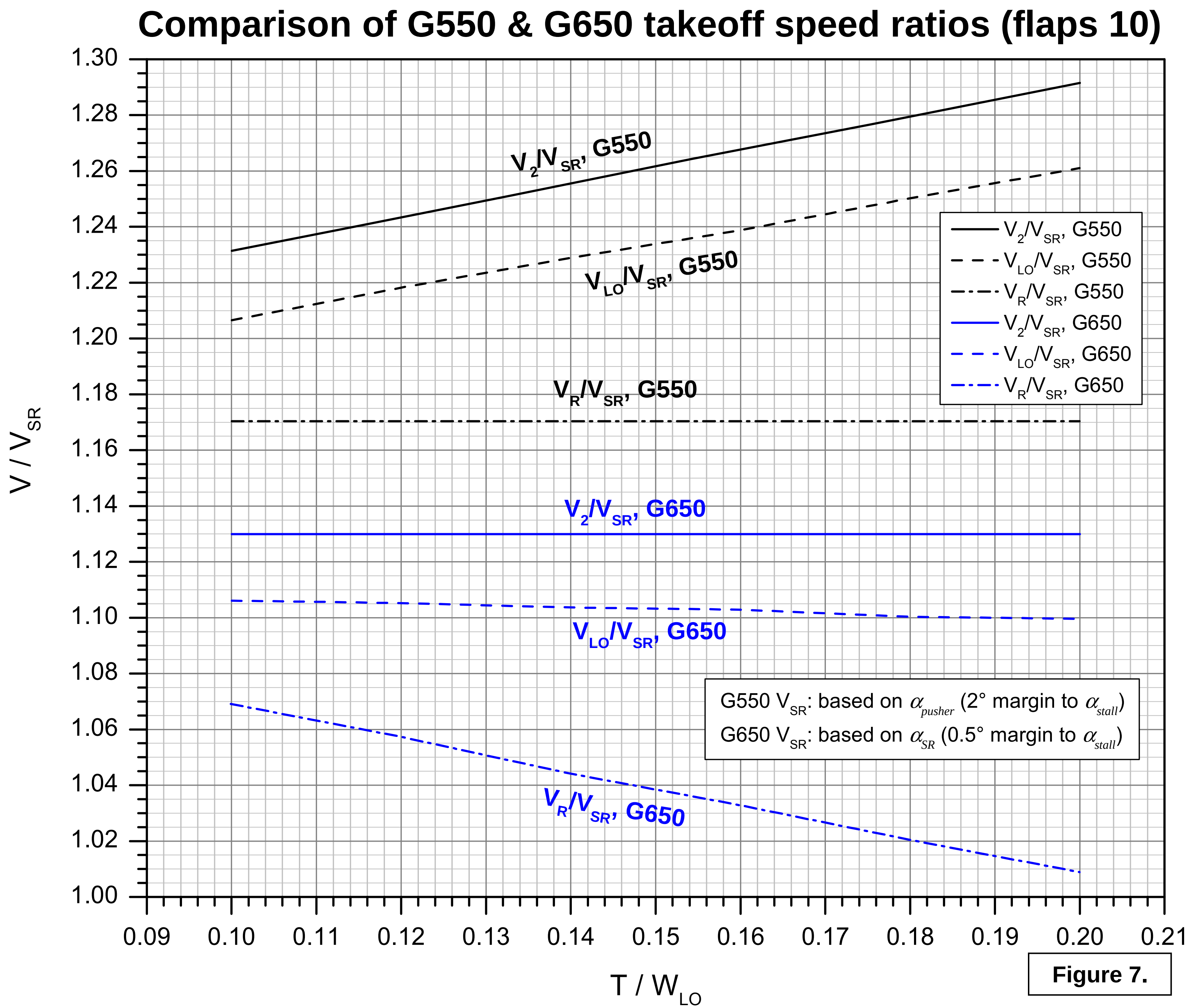

Comparison of G550 & G650 takeoff speed ratios (flaps 10)
V / V_SR
T / W_LO
1.30
1.28
1.26
1.24
1.22
1.20
1.18
1.16
1.14
1.12
1.10
1.08
1.06
1.04
1.02
1.00
0.09
0.10
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.20
0.21
V2/VSR, G550
VLO/VSR, G550
VR/VSR, G550
V2/VSR, G650
VLO/VSR, G650
VR/VSR, G650
G550 VSR: based on α pusher (2° margin to α stall)
G650 VSR: based on α SR (0.5° margin to α stall)

Figure 7.

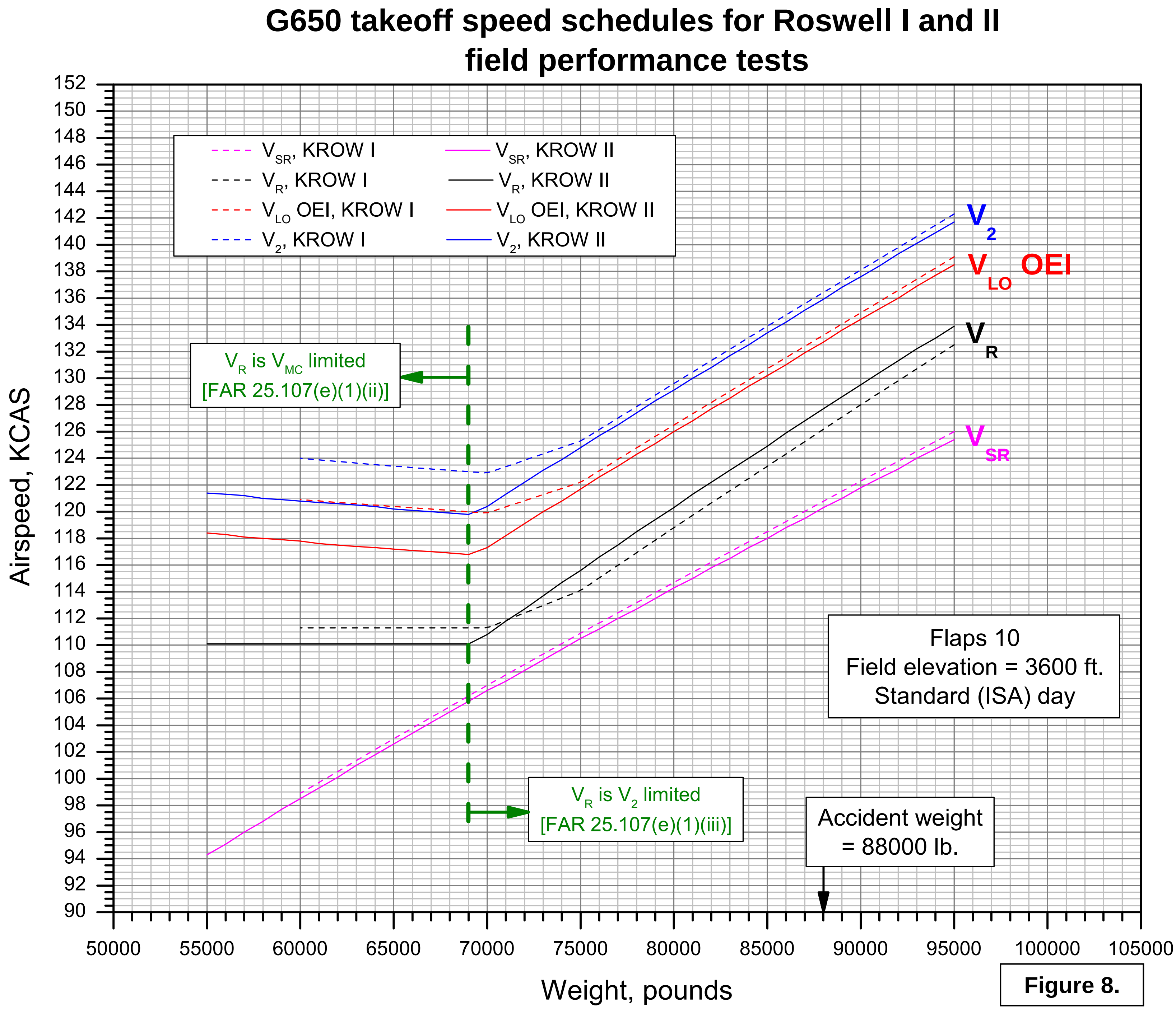

G650 takeoff speed schedules for Roswell I and II field performance tests
VSR, KROW I
VSR, KROW II
VR, KROW I
VR, KROW II
VLO OEI, KROW I
VLO OEI, KROW II
V2, KROW I
V2, KROW II
V2
VLO OEI
VR
VSR
VR is VMC limited [FAR 25.107(e)(1)(ii)]
VR is V2 limited [FAR 25.107(e)(1)(iii)]
Flaps 10
Field elevation = 3600 ft.
Standard (ISA) day
Accident weight = 88000 lb.
Airspeed, KCAS
Weight, pounds
152
150
148
146
144
142
140
138
136
134
132
130
128
126
124
122
120
118
116
114
112
110
108
106
104
102
100
98
96
94
92
90
50000
55000
60000
65000
70000
75000
80000
85000
90000
95000
100000
105000

Figure 8.

DCA11MA076: GAC G540, NG52GD, Roswell, NM, 04/02/2011
Comparison of flight 153 flaps 20 AEO runs

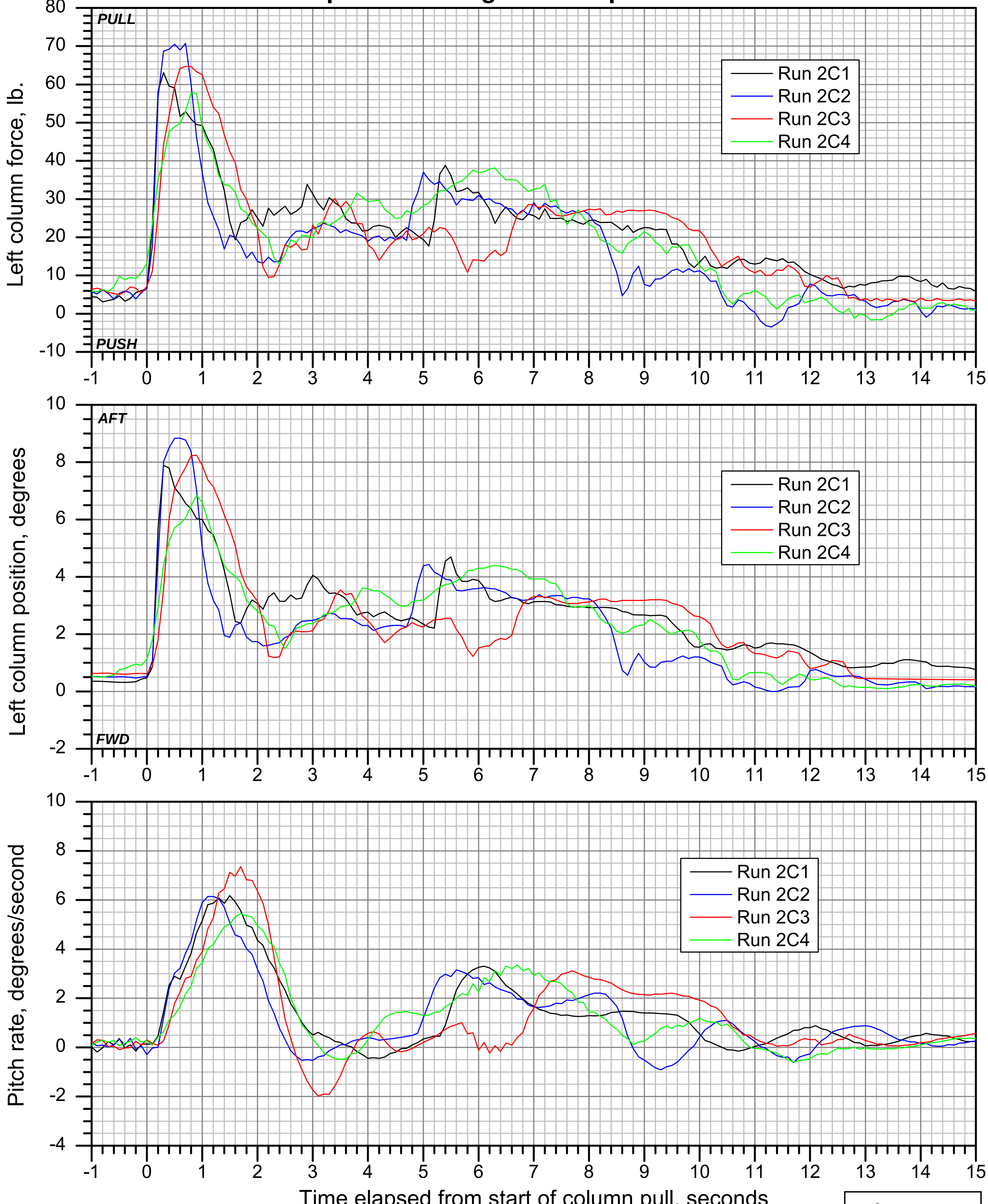


Figure 9a.

DCA11MA076: GAC G540, NG52GD, Roswell, NM, 04/02/2011
Comparison of flight 153 flaps 20 AEO runs

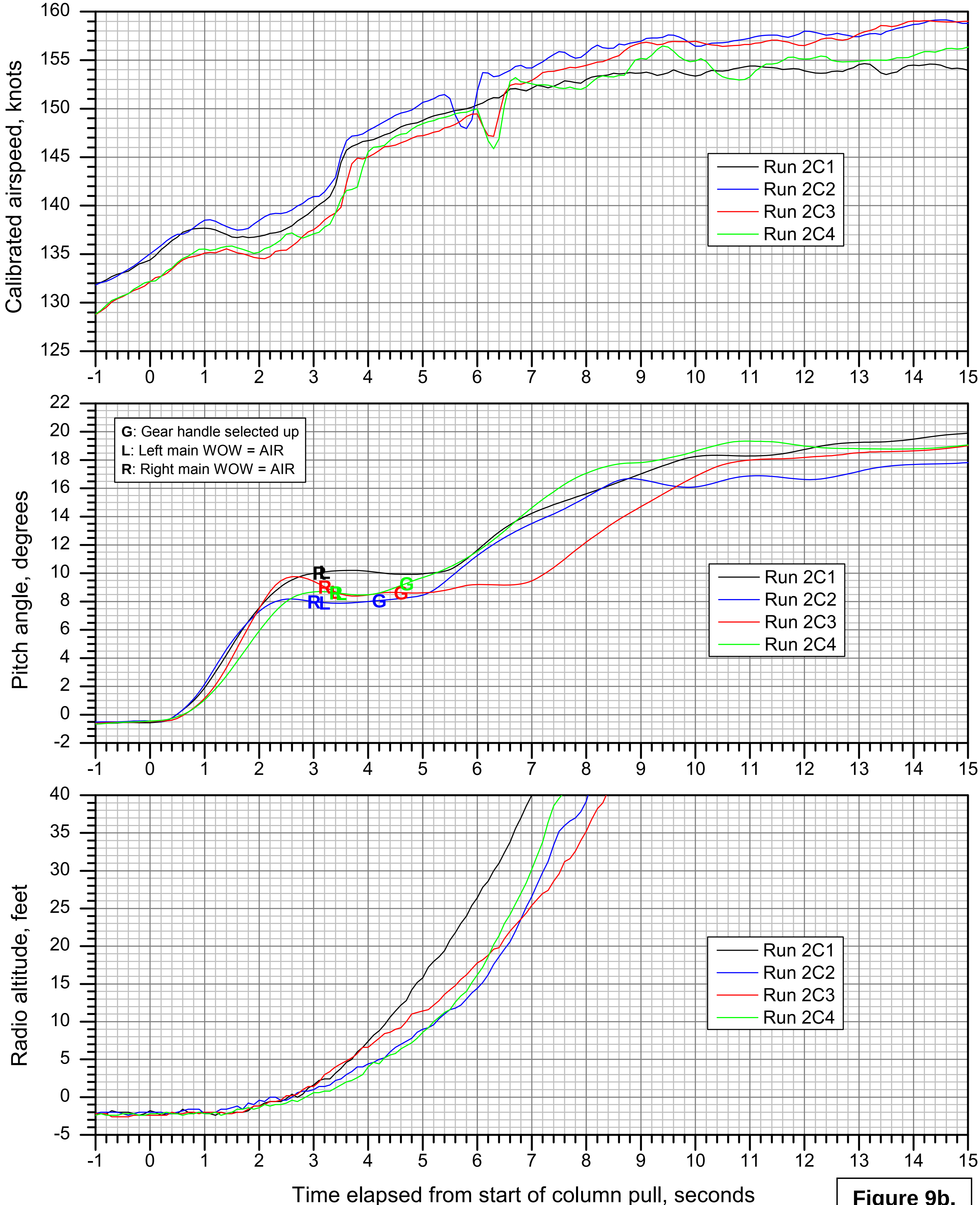


Figure 9b.

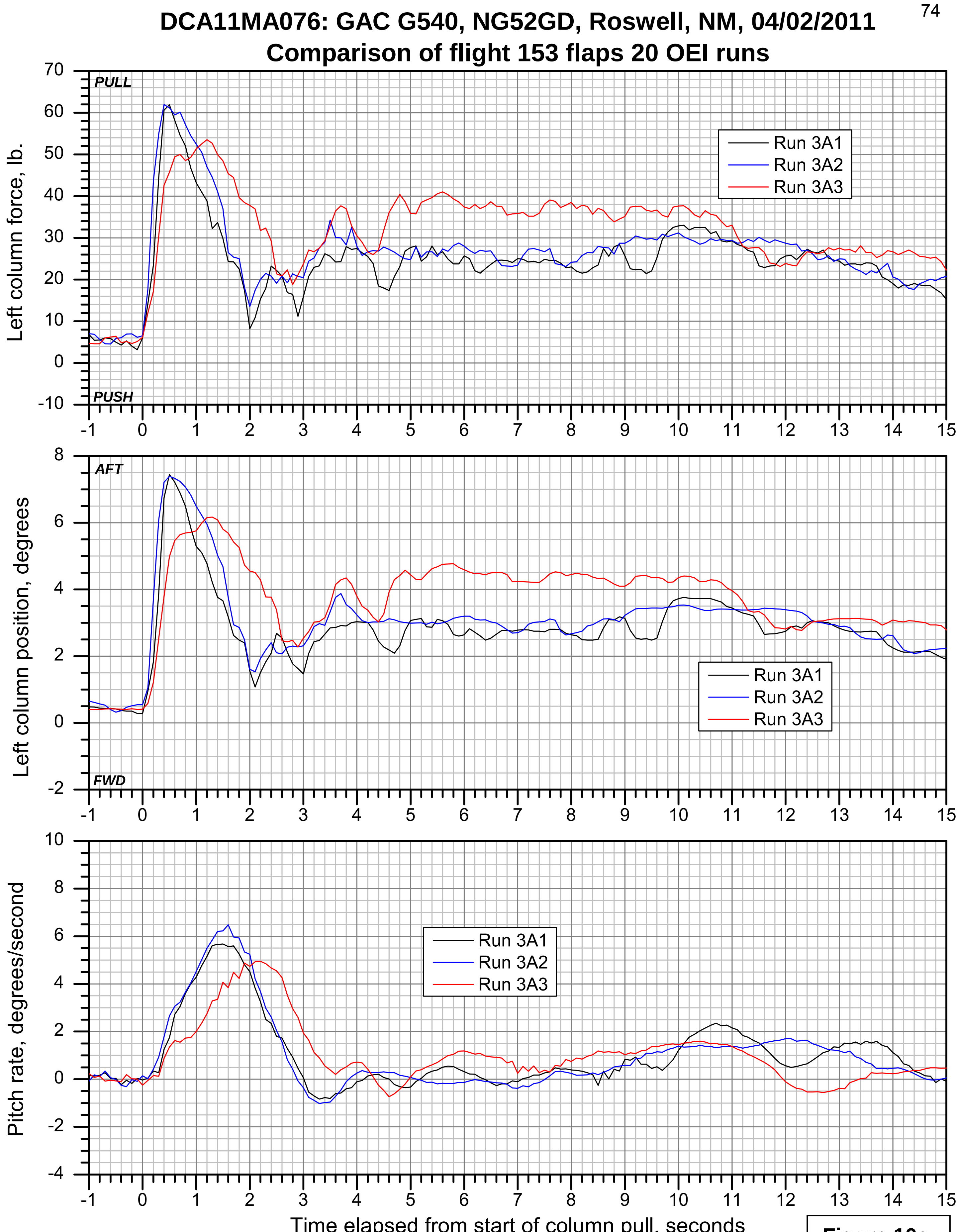

DCA11MA076: GAC G540, NG52GD, Roswell, NM, 04/02/2011
Comparison of flight 153 flaps 20 OEI runs
PULL
PUSH
Left column force, lb.
Run 3A1
Run 3A2
Run 3A3
AFT
FWD
Left column position, degrees
Pitch rate, degrees/second
Time elapsed from start of column pull, seconds

Figure 10a.

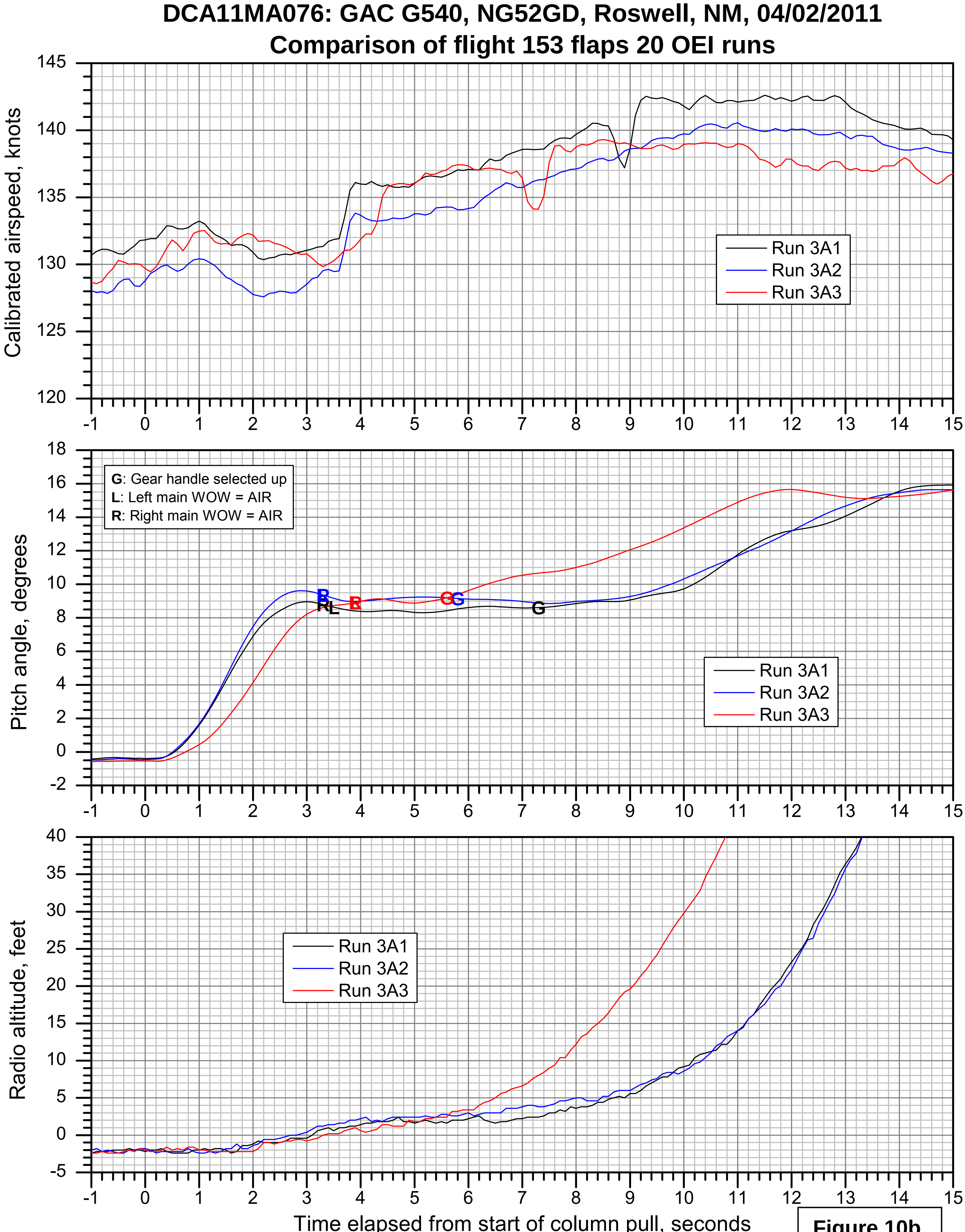

DCA11MA076: GAC G540, NG52GD, Roswell, NM, 04/02/2011
Comparison of flight 153 flaps 20 OEI runs
Calibrated airspeed, knots
145
140
135
130
125
120
Run 3A1
Run 3A2
Run 3A3
Pitch angle, degrees
18
16
14
12
10
8
6
4
2
0
-2
G: Gear handle selected up
L: Left main WOW = AIR
R: Right main WOW = AIR
Radio altitude, feet
40
35
30
25
20
15
10
5
0
-5
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Time elapsed from start of column pull, seconds

Figure 10b.

DCA11MA076: GAC G540, NG52GD, Roswell, NM, 04/02/2011
Comparison of flight 153 flaps 10 AEO runs

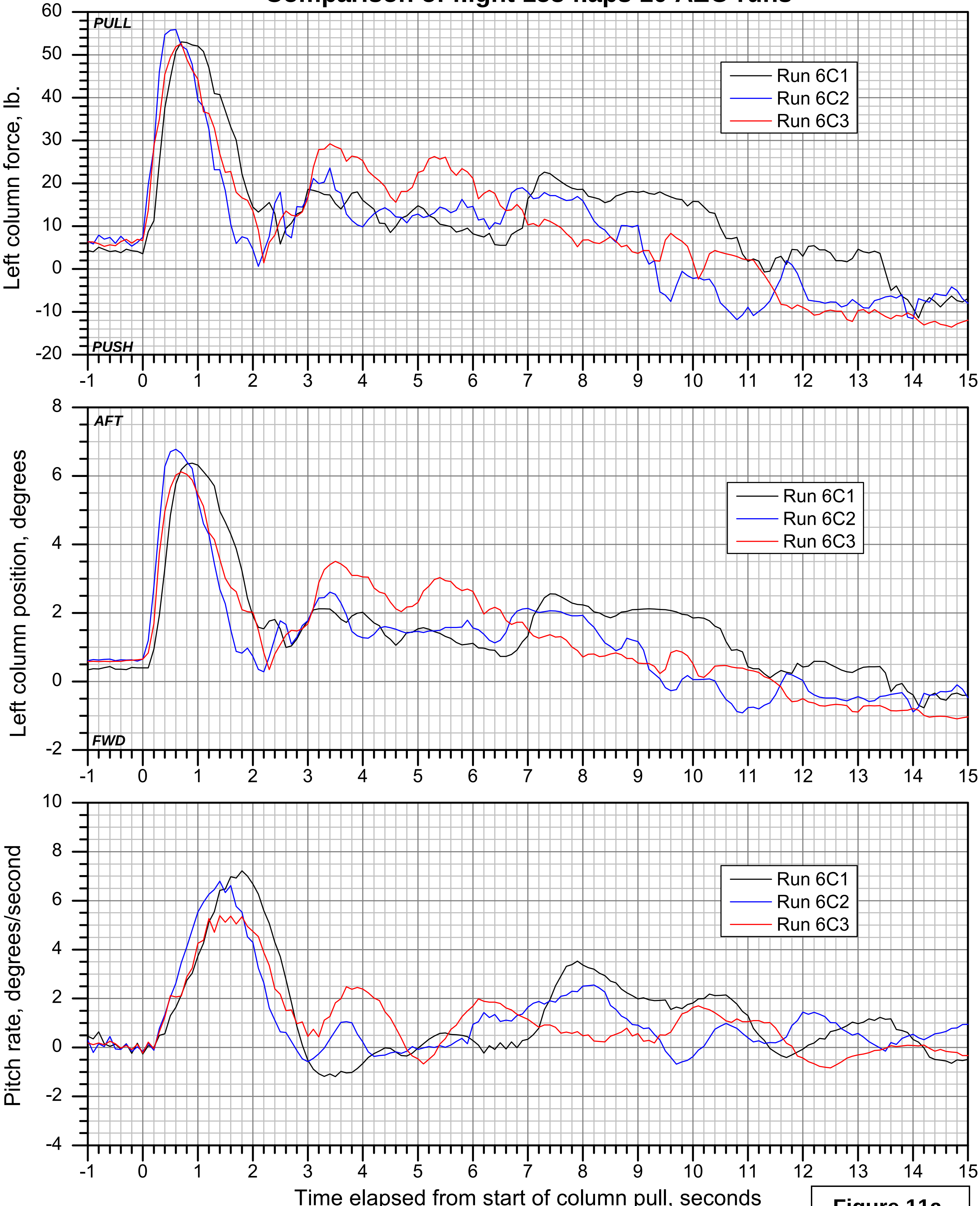


Figure 11a.

DCA11MA076: GAC G540, NG52GD, Roswell, NM, 04/02/2011
Comparison of flight 153 flaps 10 AEO runs

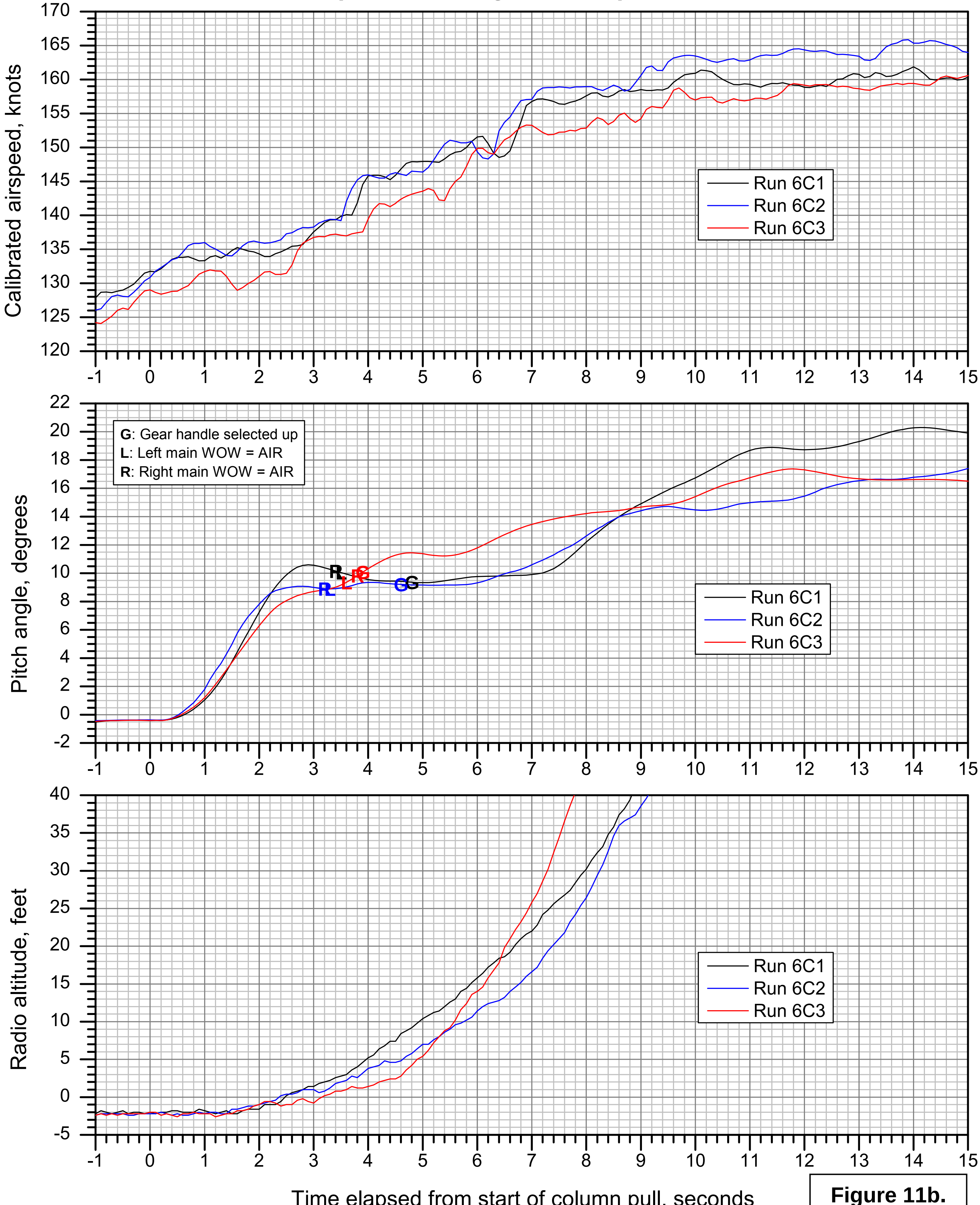


Figure 11b.

DCA11MA076: GAC G540, NG52GD, Roswell, NM, 04/02/2011
Comparison of flight 153 flaps 10 OEI runs

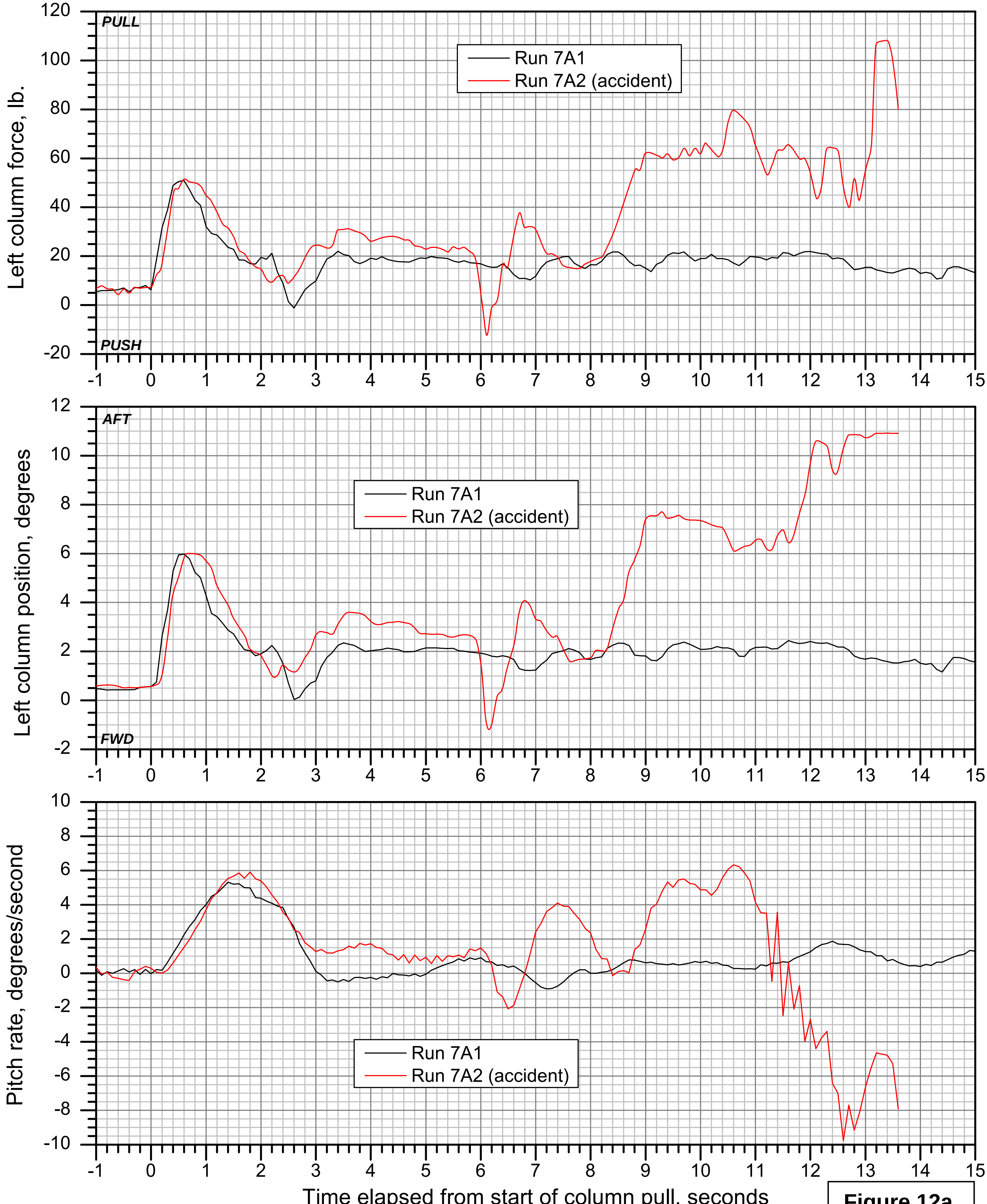


Figure 12a.

DCA11MA076: GAC G540, NG52GD, Roswell, NM, 04/02/2011
Comparison of flight 153 flaps 10 OEI runs

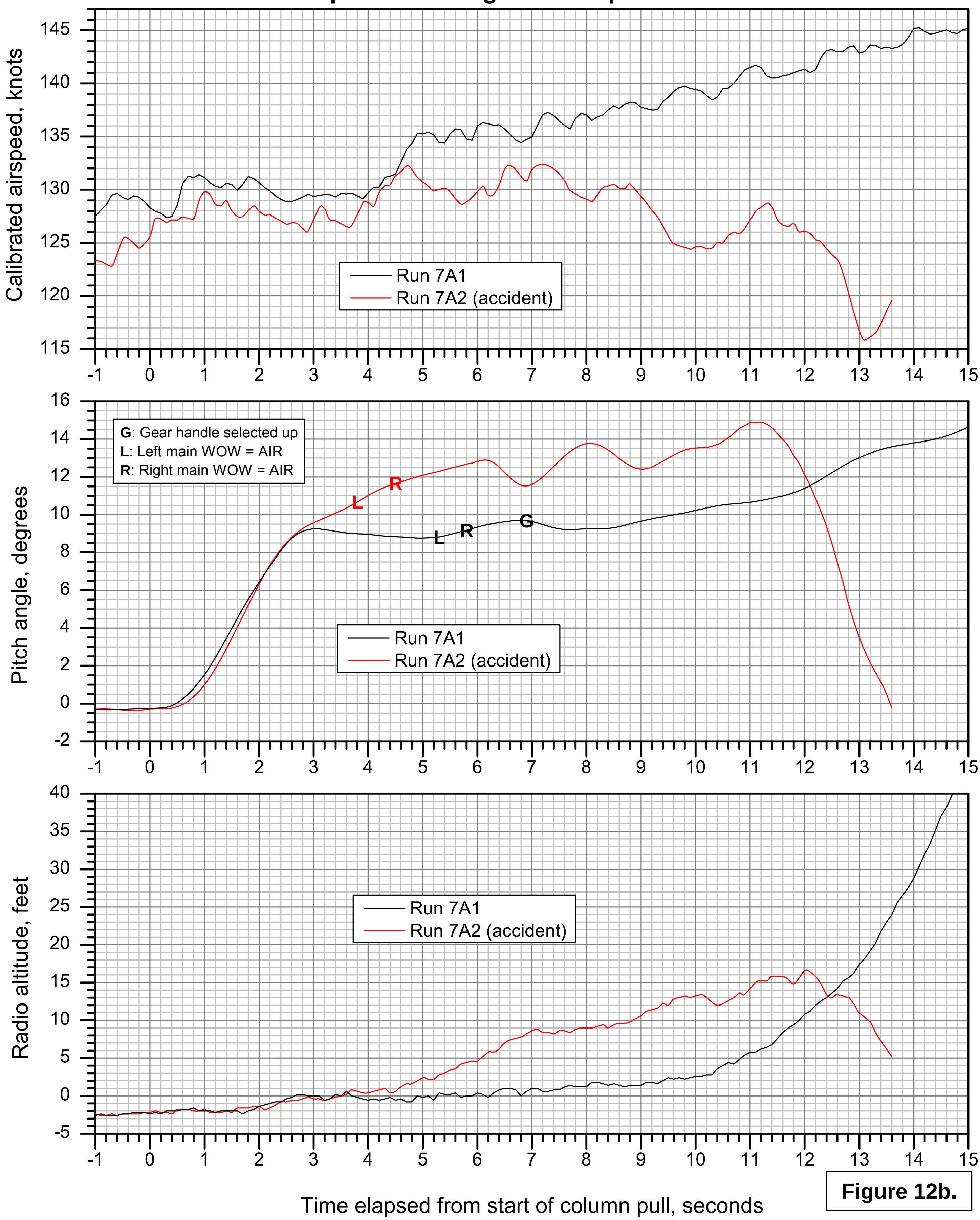


Figure 12b.

DCA11MA076: GAC G540, NG52GD, Roswell, NM, 04/02/2011
Comparison of flight 153 runs 6C3 (flaps 10 AEO) & 7A2 (flaps 10 OEI, accident)

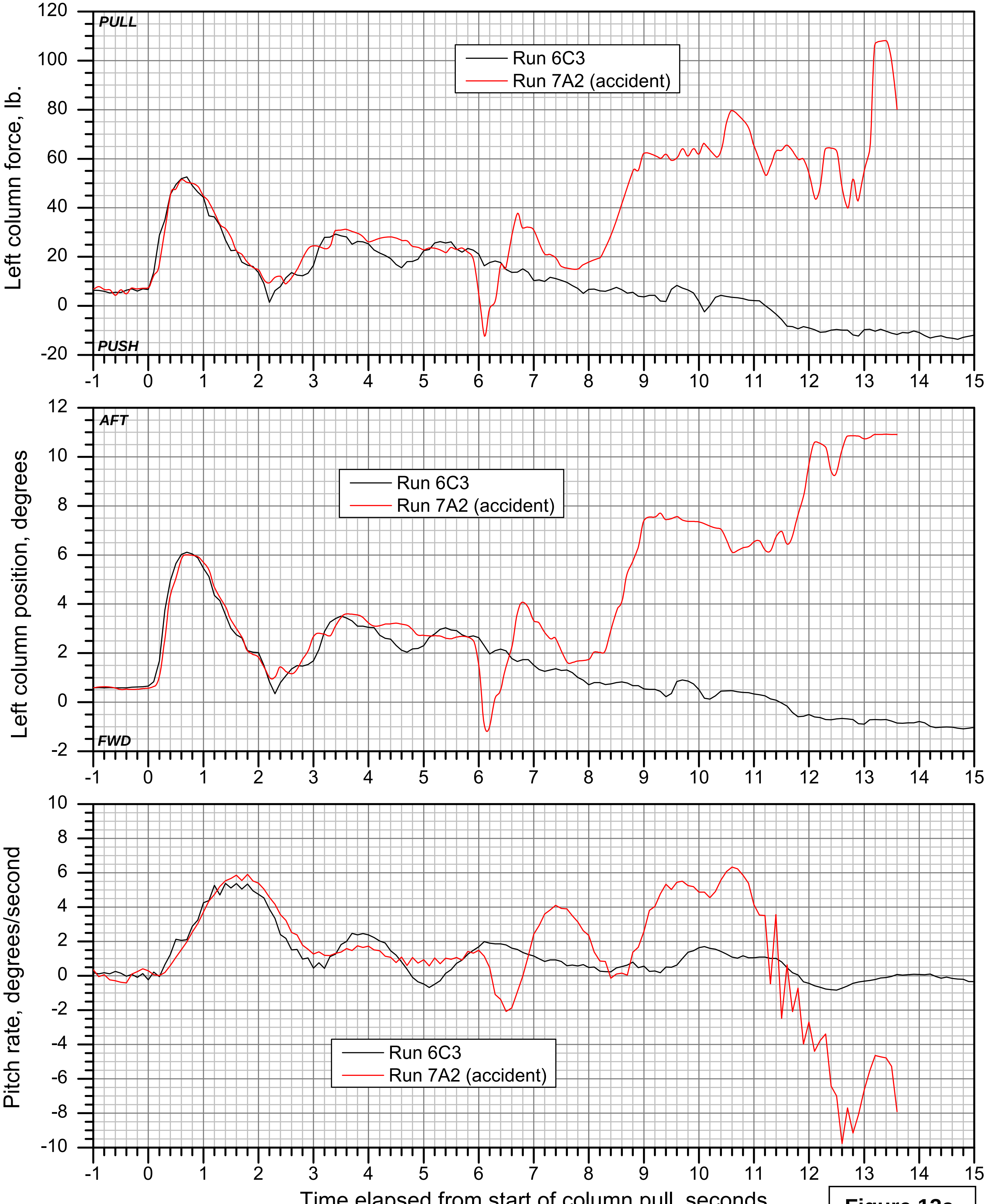


Figure 13a.

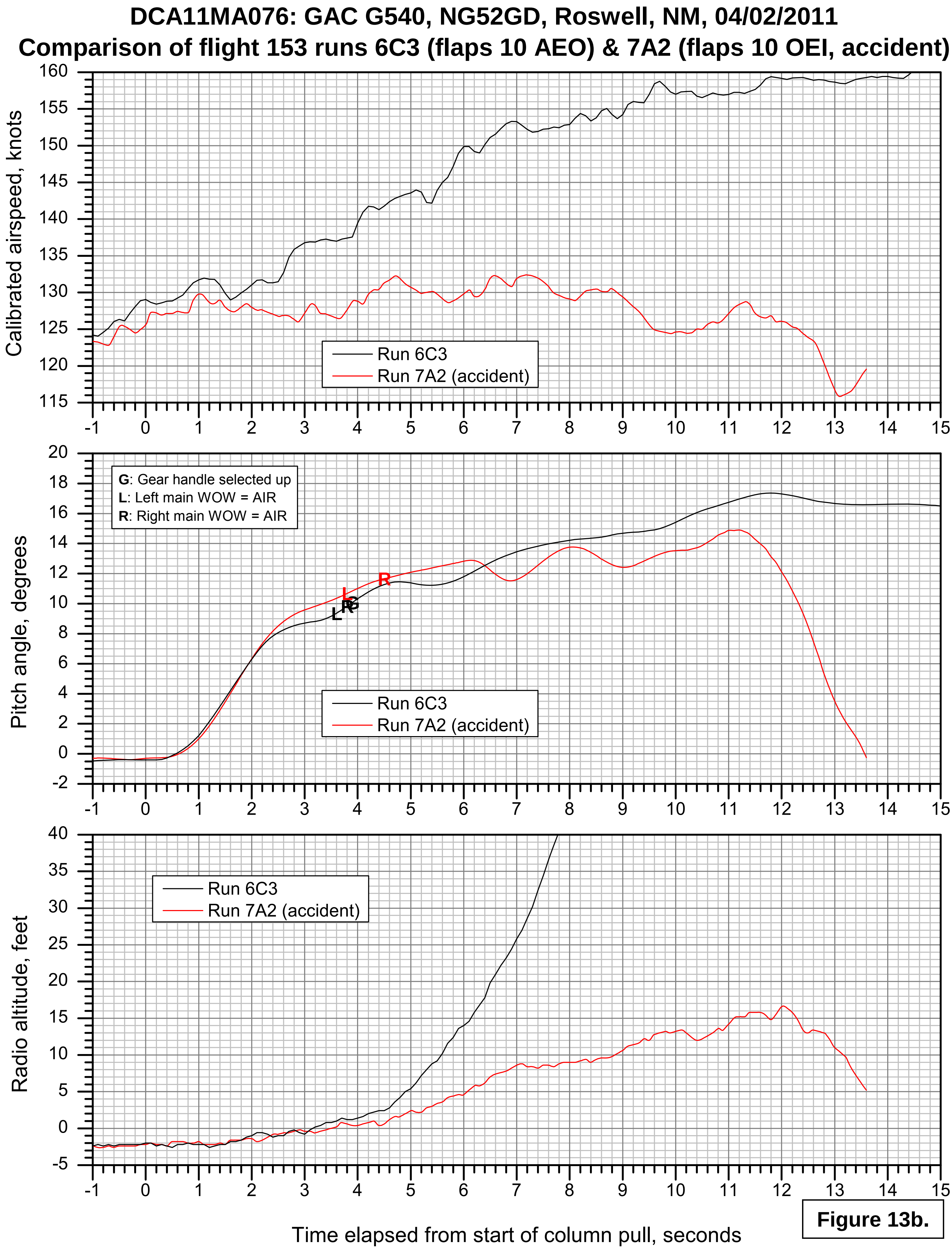

DCA11MA076: GAC G540, NG52GD, Roswell, NM, 04/02/2011
Comparison of flight 153 runs 6C3 (flaps 10 AEO) & 7A2 (flaps 10 OEI, accident)
Calibrated airspeed, knots
Run 6C3
Run 7A2 (accident)
G: Gear handle selected up
L: Left main WOW = AIR
R: Right main WOW = AIR
Pitch angle, degrees
Run 6C3
Run 7A2 (accident)
Radio altitude, feet
Run 6C3
Run 7A2 (accident)
Time elapsed from start of column pull, seconds

Figure 13b.

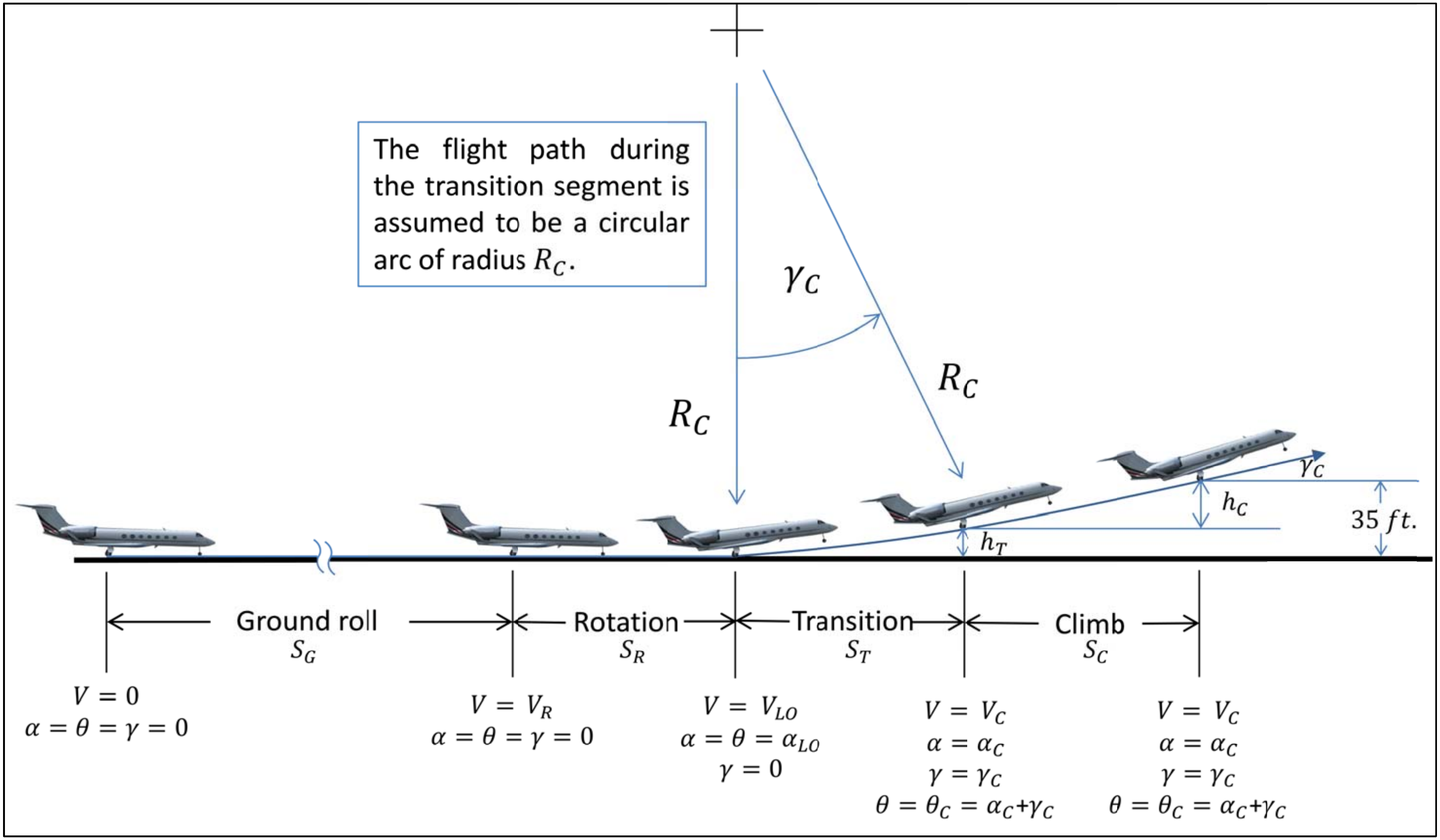


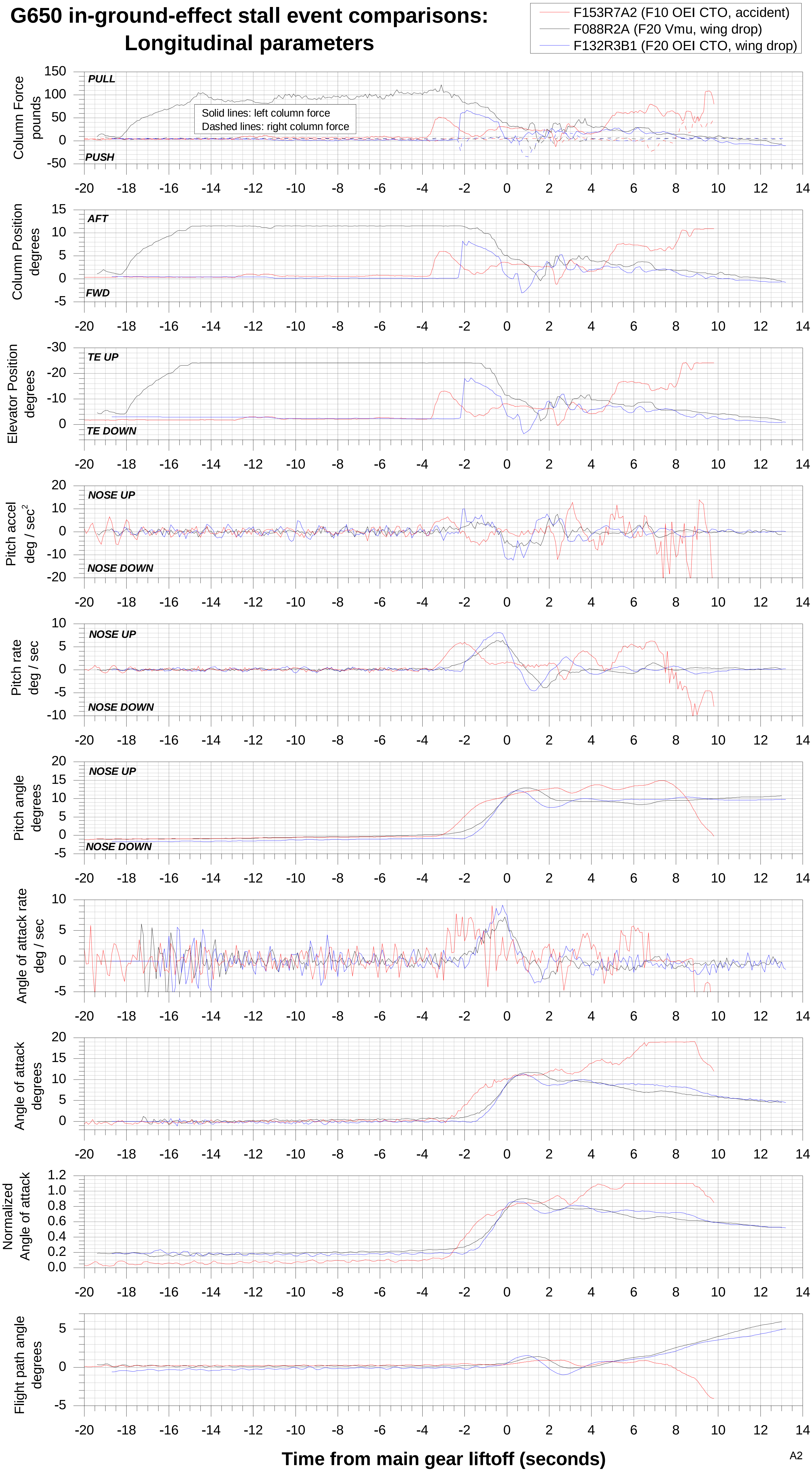
Figure 14. Takeoff segments for takeoff performance analysis.

APPENDIX A

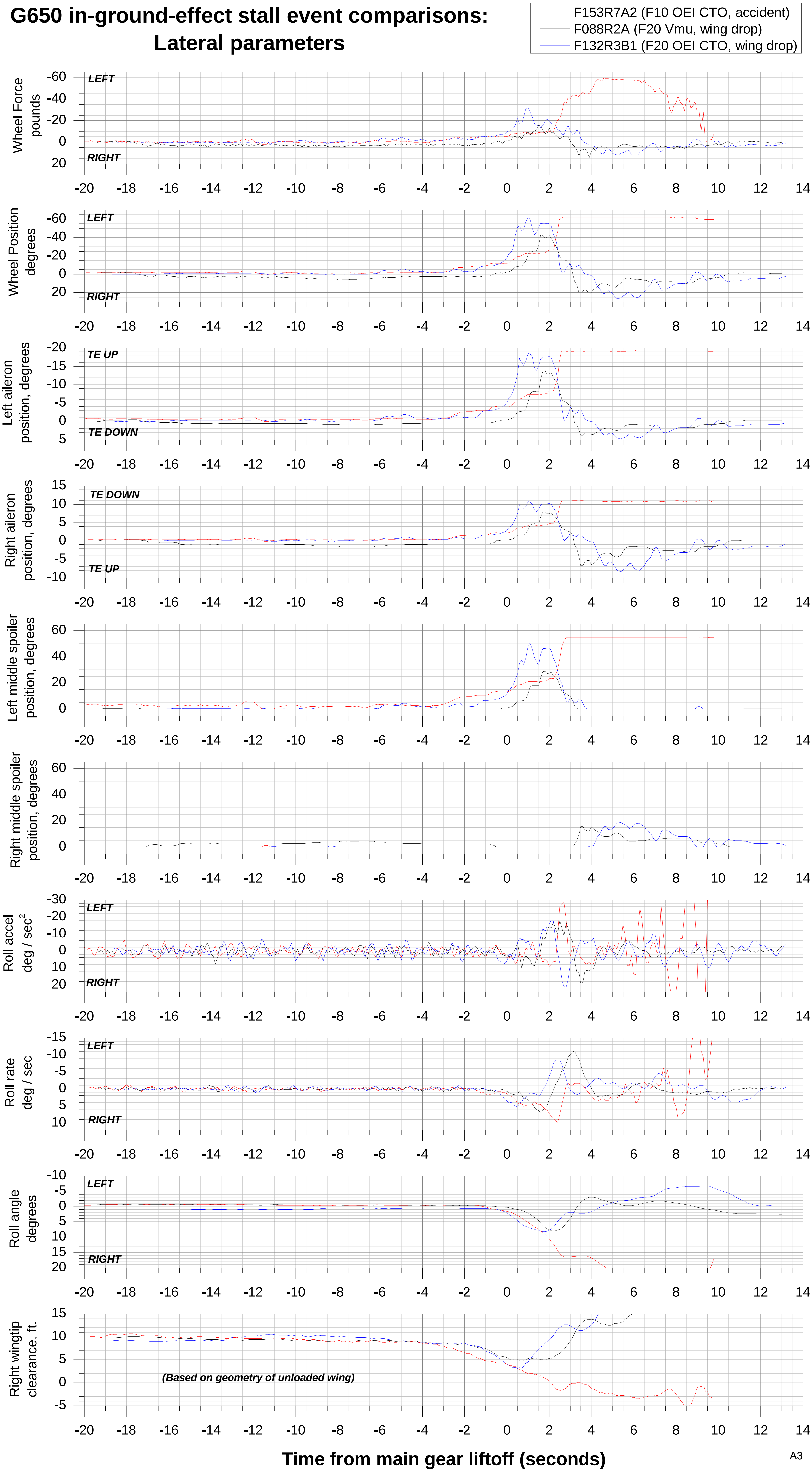
Comparison plots of:

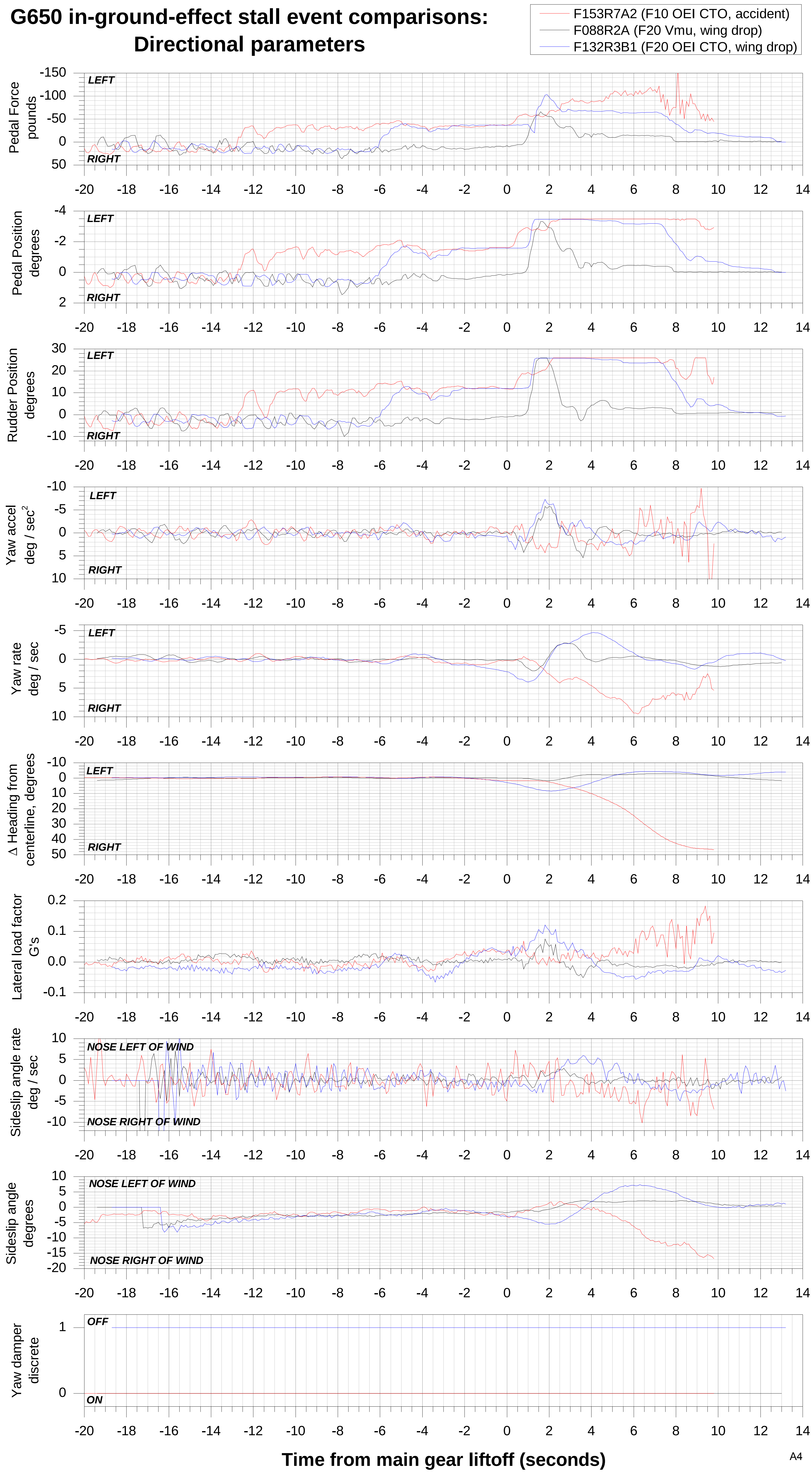
- Flight 88 Run 2A (Flaps 20 V_{MU})
- Flight 132 Run 3B1 (Flaps 20 OEI CTO)
- Flight 153 Run 7A2 (Flaps 10 OEI CTO, accident)

G650 in-ground-effect stall event comparisons: Longitudinal parameters



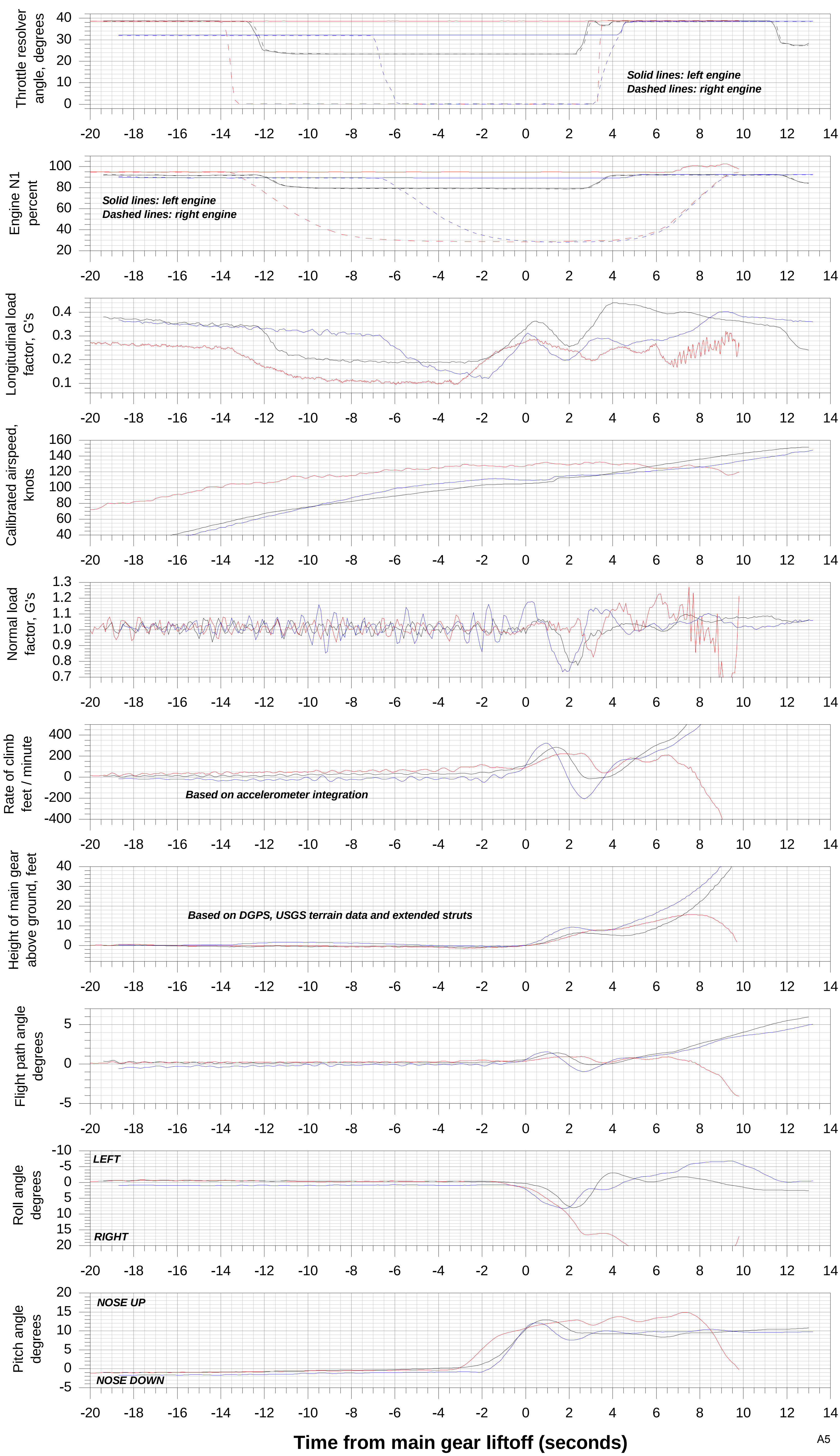
G650 in-ground-effect stall event comparisons: Lateral parameters




G650 in-ground-effect stall event comparisons:
Directional parameters
F153R7A2 (F10 OEI CTO, accident)
F088R2A (F20 Vmu, wing drop)
F132R3B1 (F20 OEI CTO, wing drop)
Pedal Force pounds
LEFT
RIGHT
Pedal Position degrees
Rudder Position degrees
Yaw accel deg / sec^2
Yaw rate deg / sec
Δ Heading from centerline, degrees
Lateral load factor G's
Sideslip angle rate deg / sec
NOSE LEFT OF WIND
NOSE RIGHT OF WIND
Sideslip angle degrees
Yaw damper discrete
OFF
ON
-20 -18 -16 -14 -12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12 14
Time from main gear liftoff (seconds)

A4

G650 in-ground-effect stall event comparisons: Energy parameters



APPENDIX B

GAC “White Paper:”

GAC Post-accident Actions for

Takeoff Airspeed Development and Testing

GAC Post-accident Actions for Takeoff Airspeed Development and Testing

Original Methodology for Take-off Performance Development

During the earlier GV program the rotation speed (V_R), lift-off speed (V_{LOF}), and take-off safety speed (V_2), were expressed as a ratio of the Reference Stall Speed (V_{SR}) and defined as a function of the aircraft's thrust-to-weight (T/W) ratio at the lift-off speed. As a general rule for the GV, V_R/V_{SR}, V_{LOF}/V_{SR} and V_2/V_{SR} increased linearly as a function of the T/W ratio. In addition, the spacing or spread between these speeds also increased with increasing T/W ratios to reflect the higher accelerations expected at the higher levels of T/W.

Legacy Gulfstream aircraft were tail power limited thus limiting the rotation speed as the aircraft approached Maximum Take-off Weight (MTOW). Design advances in the G650 provided greater tail power allowing a rotation speed, V_R, more closely aligned with the targeted aircraft safety speed, V_2. Gulfstream developed the target G650 take-off speeds prior to Roswell I and II in part by referencing the legacy aircraft airspeed ratios from the GV program, in combination with the one-G stall speed (V_{S1G}) minimums for take-off safety provided under 14 CFR Part 25. Specifically, the take-off safety speed, V_2, was assigned an assumed value at the FAA minimums provided in 14 CFR Part 25.107 for the entire range of T/W ratios. (This regulation states that the minimum take-off safety speed (V_{2MIN}) cannot be less than $1.13V_{SR}$.) The G650 rotation and lift-off speeds were developed using the speed increments between V_R/V_{SR} and V_{LOF}/V_{SR} as well as V_{LOF}/V_{SR} and V_2/V_{SR} from the GV program. These increments were expressed as a function of T/W and applied to the V_2/V_{SR} speed to obtain absolute G650 values for V_R/V_{SR} and V_{LOF}/V_{SR}.

Unlike the GV program, the resultant trend for V_R/V_{SR} and V_{LOF}/V_{SR} developed by this method decreased linearly as a function of T/W. Effectively, the V_R and V_{LO} speeds were decremented to guarantee a take-off safety speed of $1.13V_{SR}$ at all values of T/W. At the higher values of T/W this methodology established ratios of V_R/V_{SR} at values which approached unity, or the Reference Stall Speed.

Absolute speeds for V_R, V_{LO} and V_2 in terms of Calibrated Airspeed were developed using the published values for the Reference Stall Speed, which had been initially validated earlier during company flight testing. The resulting take-off speeds were adopted directly for the field performance flight test program during the Roswell I and II testing. Take off speeds were developed for specific initial pitch attitudes for flaps 10 and 20. These were utilized during Roswell I testing. Prior to Roswell II testing, the initial pitch attitude for flaps 10 was reduced to align with the flaps 20 initial pitch target while retaining the same takeoff speeds.

During the testing at Roswell, the pilots noted time delays of several seconds between V_R and V_{LO}, especially during the single engine take-off phase of testing and particularly in the flap 10 configuration, an alternate take-off configuration proposed for high altitude/high temperature operations. Throughout this phase of testing, the aircraft continually overshot the predicted lift-off speed and take-off safety speed using the targeted pitch attitude at rotation. Post-accident analyses indicated that the V_{LOF} and V_2 take-off speeds for this testing were too slow, and the spacing between V_R, V_{LOF} and V_2 was too narrow. Analyses also revealed that the flap 10 V_R speeds were several knots too slow for single engine take-off operations.

A post accident review of the aircraft take-off maneuvers during flight testing, and the methodology employed to develop these airspeeds, revealed the following problem areas with the take-off speed development and flight test methodology being employed at the time of this testing:

- G650 take-off speeds were developed based on the performance characteristics of legacy aircraft and were factored to the FAA-regulated minimum requirements for safety speed in order to minimize balanced field length. The speeds were not verified or validated prior to flight testing.

- The analytical tool used to develop takeoff field performance parameters was deficient in that it relied on empirical data from legacy aircraft. In addition, the tool lacked the capability to assess alpha margins and to accurately model aircraft dynamics.

- During Roswell I and II testing, when the test crews experienced difficulties achieving the target V2 speeds, they began to refine the takeoff technique in an attempt to capture the target speeds. Further examination of the established target speeds was not performed.

Improved Methodology for Take-off Performance Development

Following the accident, a new methodology was developed to address the shortcomings identified above. This new technique employs a four part approach to develop a set of useable airspeeds for take-off performance within Engineering before flight testing is begun and to safely verify these speeds during subsequent testing.

Desktop Speed Synthesis and Field Performance Evaluation

The new method proposed at Gulfstream for airspeed development does not employ legacy airspeed data, but instead generates airspeeds using a 3 degree-of freedom desktop simulation that represents the dynamics of the maneuver, the aerodynamics of the aircraft in and out of ground effect, and the control effectiveness present in a particular aircraft. This desktop simulation has been developed to more precisely model the take-off maneuver and predict representative take-off safety speeds. This method numerically solves the equations of motion to properly model the physics of the take-off, including the dynamics of the maneuver between lift-off and obstacle clearance height. The algorithm is rigorously benchmarked against existing flight test data to ensure it more precisely modeled the dynamics of the aircraft. Once benchmarking is completed, the program is used to develop a set of take-off speeds that ensure, among other considerations: 1) an achievable and repeatable initial pitch attitude is ensured at rotation and 2) a suitable margin between the operating angle of attack and the stall angle of attack during ground effect operations and climb out to obstacle clearance height. These final airspeeds are designed to guarantee a specific stall margin during all engine take-offs, single engine take-offs, and abused take-offs as prescribed in the Flight Test Guide (AC-25-7A/B). Within the algorithm, the final airspeeds are also checked to always ensure that the regulatory margins relative to V_{MU}, V_{MCG}, and V_{SR} are satisfied.

Integrated Pilot-in-the-Loop Simulation for Speed and Technique Validation

This new approach to take-off speed development also uses the G650 Integrated Test Facility (ITF) to validate the take-off speeds developed at the desktop level in a pilot-in-the-loop environment. The ITF is a fixed base flight simulator, which integrates a six degree of freedom numerical simulation of the aircraft dynamics with actual aircraft hardware, allowing pilot training and technique development for hazardous testing within the safety of a laboratory environment. The G650 ITF is thoroughly benchmarked against flight test maneuvers performed during the company flight test program to ensure that it correctly models the aircraft dynamics.

The ITF is now being employed in a dual role to help in the development of the G650 take-off speeds. The first is the development and verification of a suitable and repeatable pilot technique, which allows the aircraft to safely rotate to the initial pitch attitude and to lift-off and climb-out through obstacle clearance height without requiring exceptional pilot skill. In this capacity, a technique was developed, tested and verified using multiple Gulfstream pilots and several FAA pilots performing controlled all-engine and single engine take-offs using this pilot-in-the-loop simulation in the safety of a laboratory environment before migrating the technique onto the flight test aircraft.

In a secondary (but equally important) role the ITF is used to verify that the aircraft will operate as predicted in the desktop simulation at a number of airfield elevations (from Sea Level to 9000 ft) and across all aircraft take-off weights. This secondary task provides a verification of the established take-off speeds prior to the start of field performance testing.

In Ground Effect Stall Warning

During post-accident safety reviews, an extensive CFD study was conducted to identify changes in aerodynamic stall due to the proximity of the aircraft wing to the ground. A primary result of this effort was the characterization of stall angle of attack as a function of height above the ground. Initially, this information was used to more precisely define takeoff speeds and later was employed to generate safety of flight angle of attack margins to be used in flight testing. These are monitored in real time both on board the aircraft as well as by a ground support crew of engineers in the telemetry trailer. As an effort to improve safety and pilot awareness, a flight test aid was developed in the Flight Control Computer (FCC) utilizing the G650 radio altimeters to indicate height above the ground. By knowing the height above the ground and air data Mach number, ground effect stall angle can be computed. Combining this with a suitable margin to stall, the FCC can drive the pitch limit indicator (PLI) on the attitude indicators on both the primary flight display (PFD) and the heads up display (HUD) providing the pilots with an unprecedented level of ground effect situational awareness. Lastly, in the event the aircraft angle of attack encroaches upon this margin to stall, the FCC will then activate the stall warning stick shaker.

Flight Test Procedure for Airspeed Verification

During field performance testing, additional engineering specialists supporting flight testing are located on-site at telemetry stations for improved real-time monitoring and analysis of the general handling characteristics of the aircraft during all phases of the take-off testing. These engineers utilize two dissimilar real-time desktop simulations to predict the aircraft characteristics for each maneuver being flown and provide the expected minimum margins to aerodynamic stall. Prior to the start of each take-off run, estimates of the minimum margins are developed by each simulation, compared for validity, and properly communicated to the crew on the test aircraft before the aircraft is released for take-off. As an additional level of safety, a build-down to the published take-off speeds during the initial phase of each take-off test was implemented. If during this phase the aircraft shows abnormal handling qualities, reduced acceleration during the ground roll and/or excessive air phase or climb out times than predicted by the on-site desktop estimates, testing shall be halted and the data thoroughly reviewed. If the cause of any abnormal characteristics cannot be immediately identified and corrected, testing shall be halted until the phenomenon is satisfactorily explained.

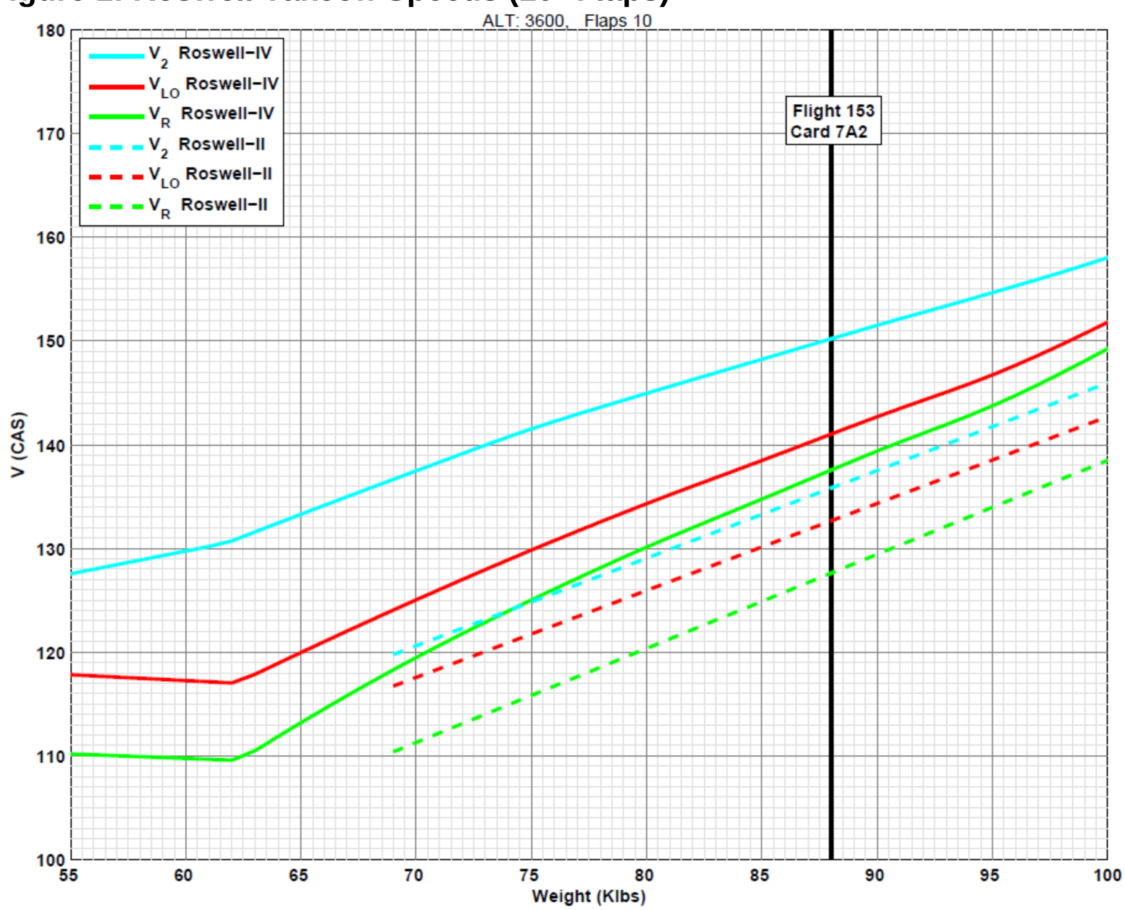
Final Comments

This four-tiered approach to define a safer and more accurate method for take-off airspeed and pilot technique development was tested during the Roswell IV company field performance testing performed approximately 10 months after the 6002 accident. The basis for this later testing was the verification of a set of take-off speeds developed utilizing the improved methodology implemented at Gulfstream following the accident. These latest take-off speeds are defined by the solid lines in Figure 1 for flap 10 take-offs and Figure 2 for the flap 20 configuration.†

The results of the Roswell IV flight tests provided excellent agreement with the predictions for the airspeeds, field lengths and angle of attack margins. The aircraft responded as both the desktop simulations and ITF predicted and at no time were any problems noted by the flight crew regarding general handling of the aircraft or the ability of the aircraft to lift-off and safely reach obstacle clearance height. This new approach has been proven to provide a safe, systematic and physically accurate method that will be utilized by Gulfstream for future aircraft development.

Figures

Figure 1: Roswell Takeoff Speeds (10° Flaps)



† The dashed lines in Figures 1&2 represent the take-off speeds used at the time of the 6002 accident and are provided for comparison purposes.

Figure 2: Roswell Takeoff Speeds (20° Flaps)